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ATLAS+CMS combined H boson mass measurement, search for offshell decays and for high-mass scalars

ICNFP 2015
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Pascal Vanlaer, Université Libre de Bruxelles
on behalf of the ATLAS and CMS collaborations

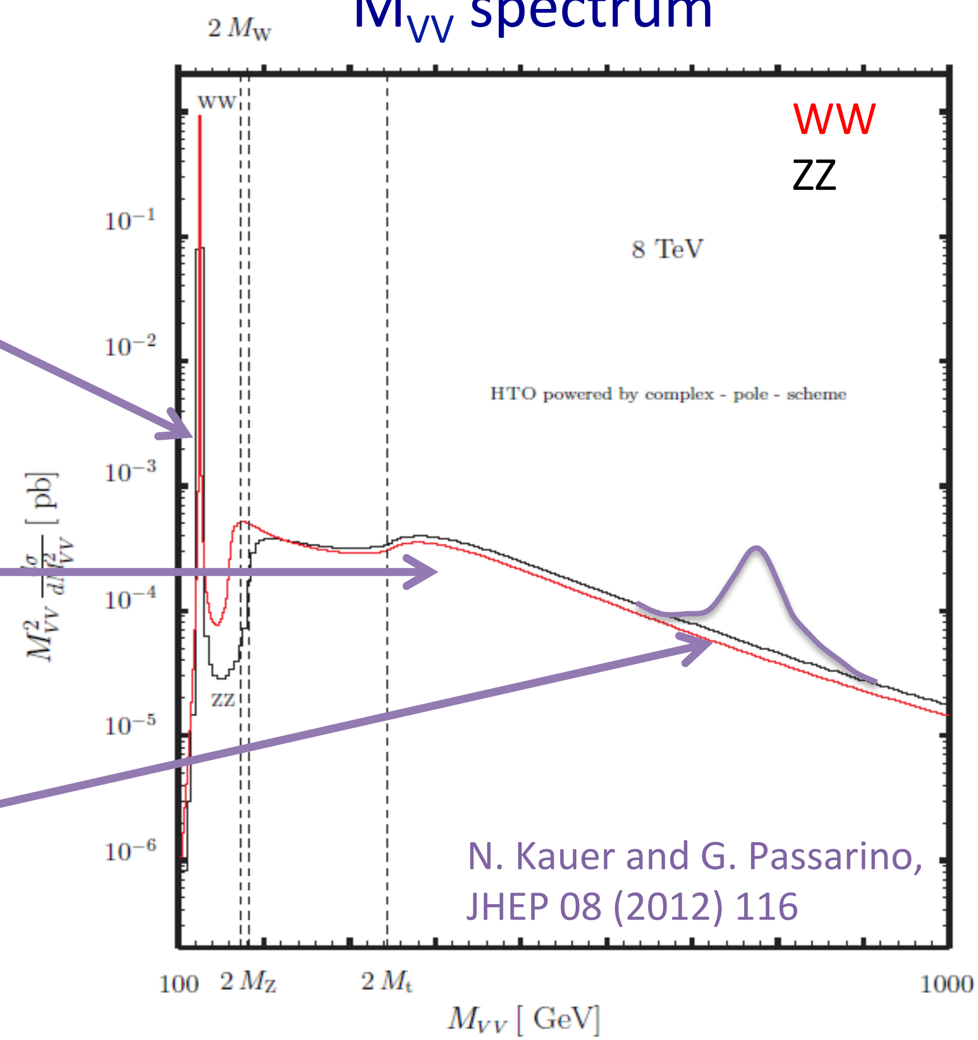
Outline

1) Combined ATLAS+CMS measurement of H boson mass in the H->ZZ->4l and H->γγ channels

2) Search for offshell H boson decays

3) Search for additional high-mass scalars

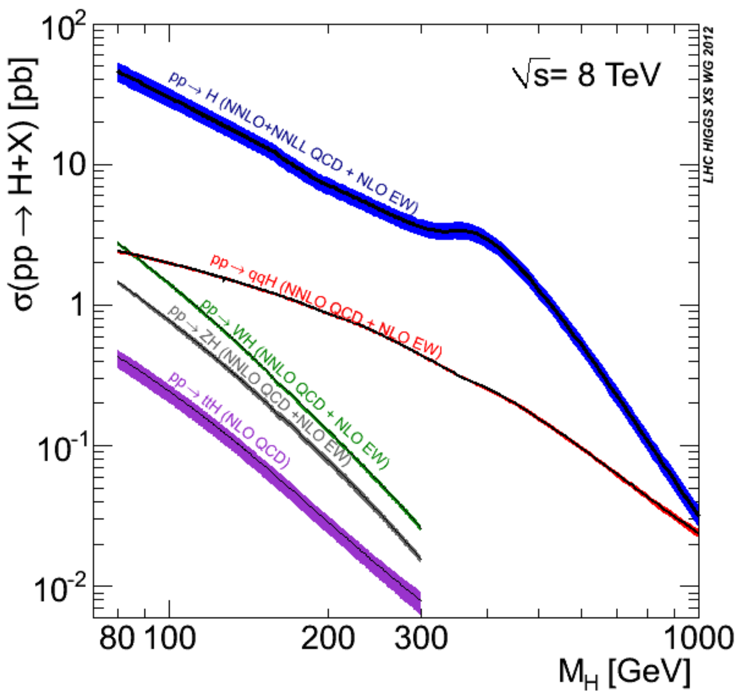
M_{VV} spectrum

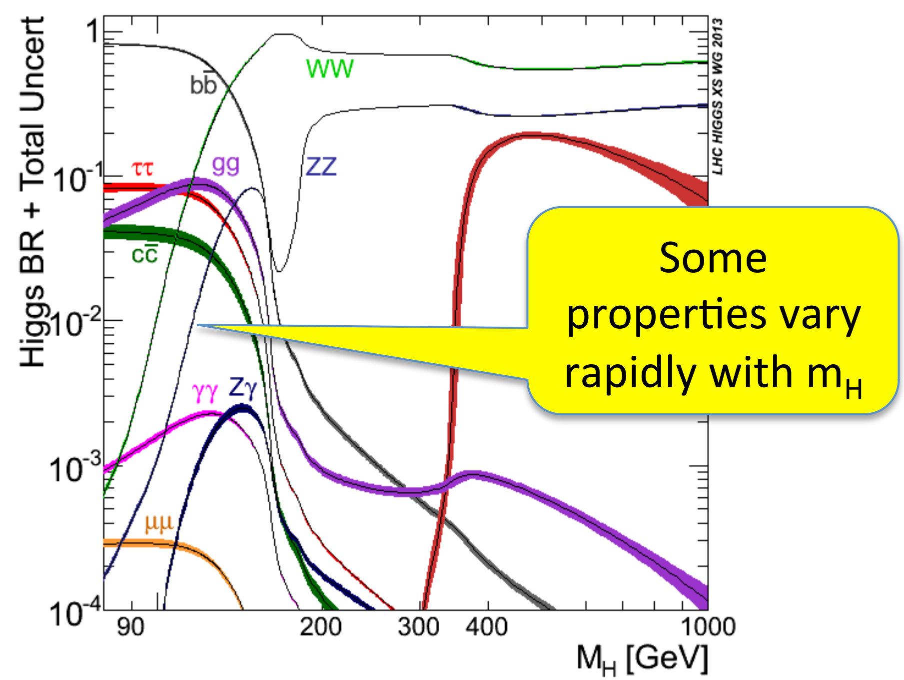


N. Kauer and G. Passarino, JHEP 08 (2012) 116

H boson mass

- **m_H is a free parameter of the Standard Model**
- It is measured precisely by ATLAS and CMS in the H->ZZ->4l and H->γγ channels (1-2% mass resolution)
- Once m_H is known, all SM H boson properties are predicted (couplings, production cross sections, decay branching fractions, …)

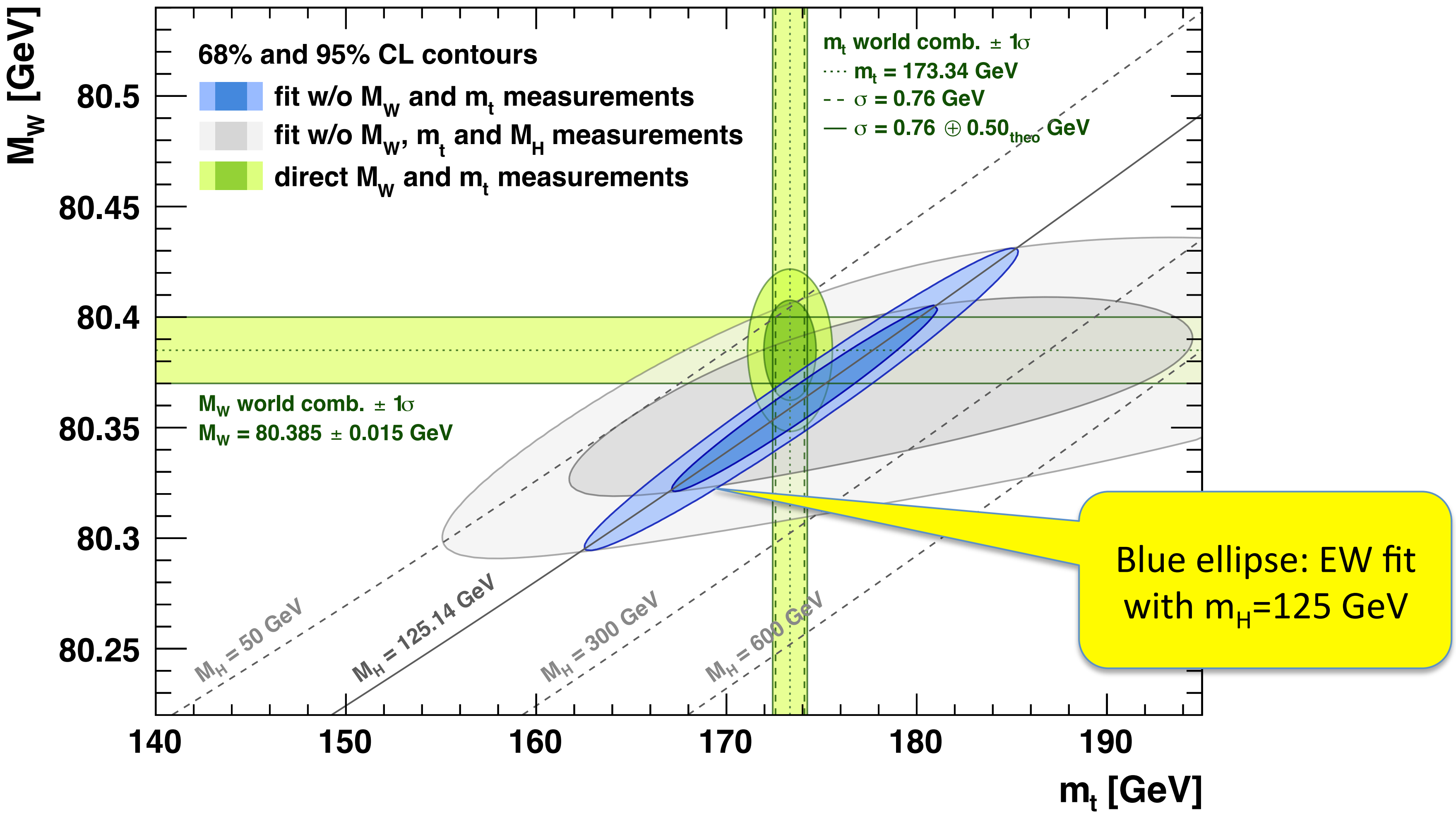




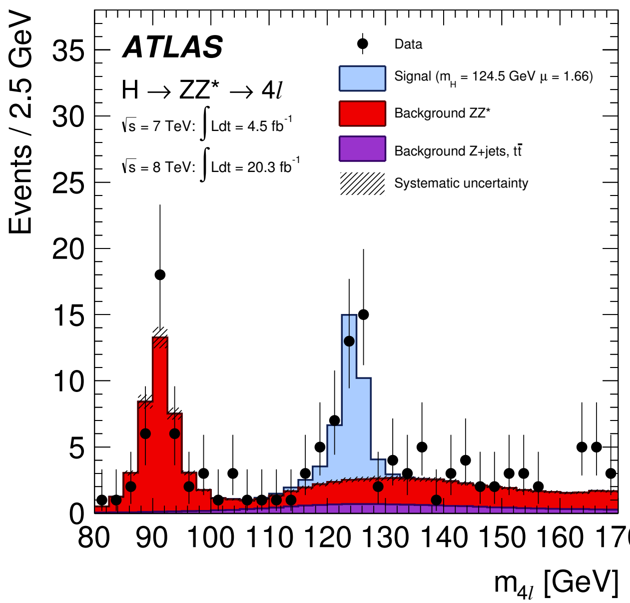
Consistency tests of SM parameters

- Direct measurements vs. fits to EW precision observables

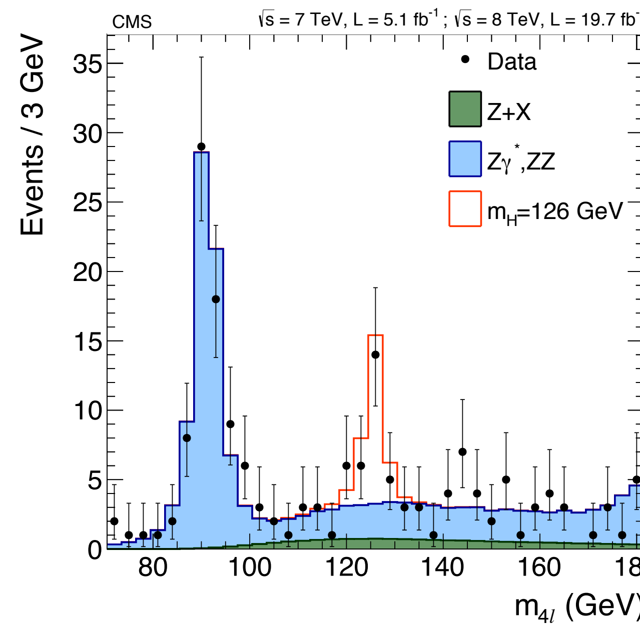
arXiv:1407.3792v1



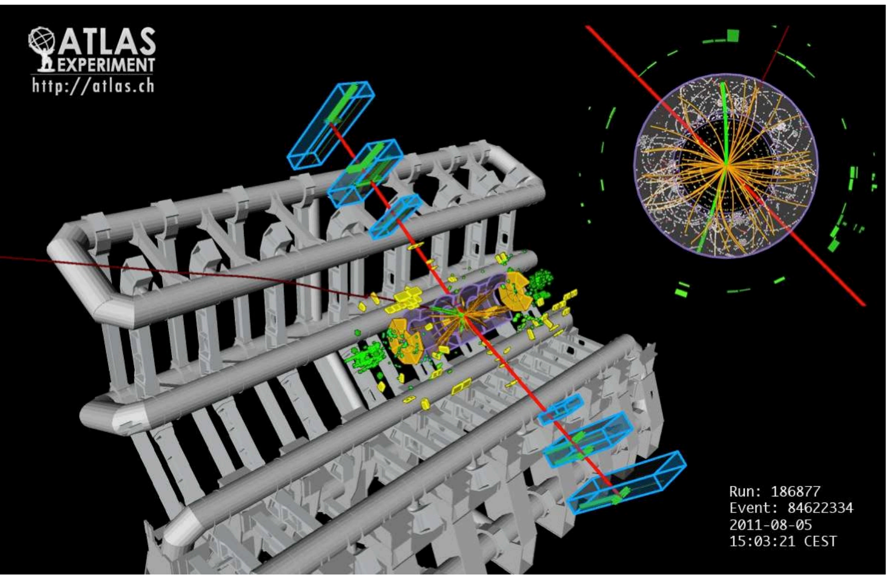
H->ZZ->4l channel

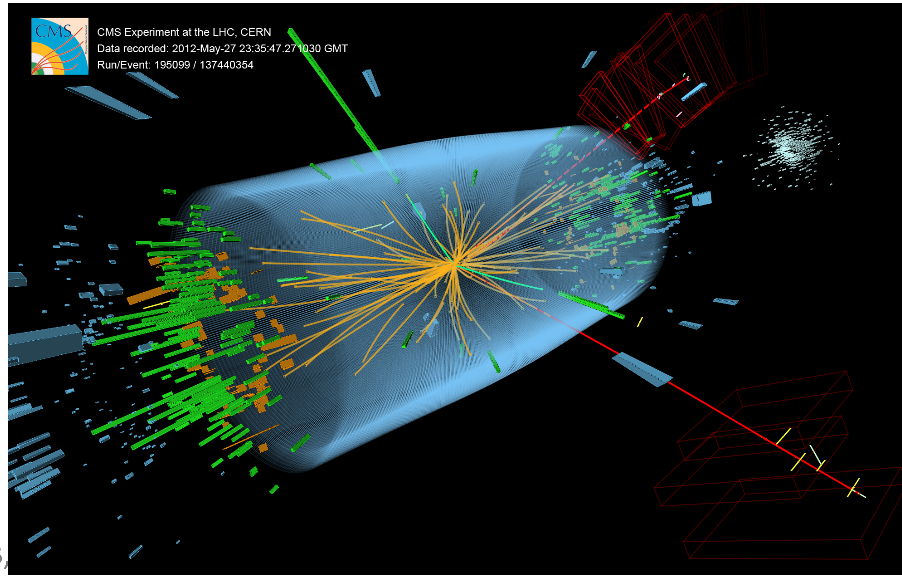


Phys. Rev. D 91, 012006 (2015)



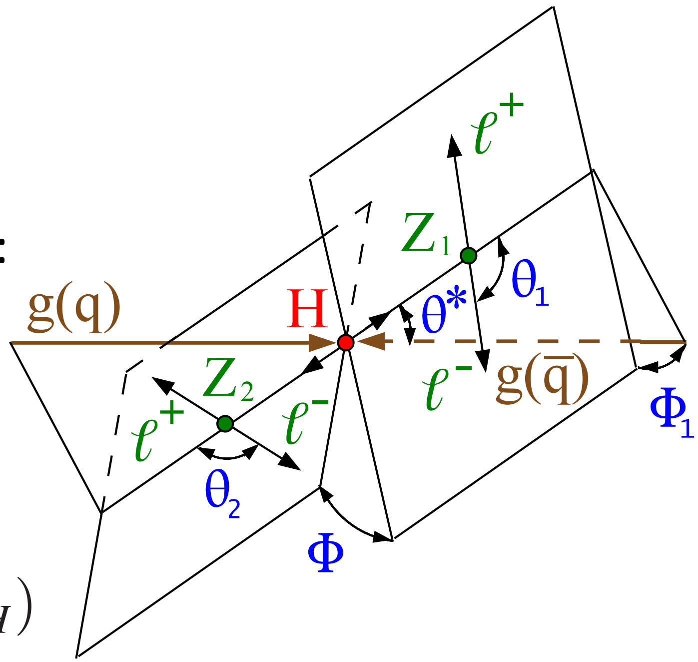
Phys. Rev. D 89, 092007 (2014)





Analysis

- **Two pairs of leptons (electrons or muons)**, isolated and prompt, of opposite sign and same flavor, selected down to low p_T (~5 GeV)
- Requirements on di-lepton masses



Kinematic discriminants:

- 7 variables completely describe decay kinematics:
  m_{Z1}, m_{Z2}, 5 angles
- Probability distributions are built from matrix elements for various contributing processes (gg → 4l signal, gg → 4l total, qq → 4l etc.) e.g.

$$\mathcal{P}_{J^P} = \mathcal{P}^{\text{kin}}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell}) \times \mathcal{P}^{\text{mass}}_{\text{sig}}(m_{4\ell} | m_H)$$

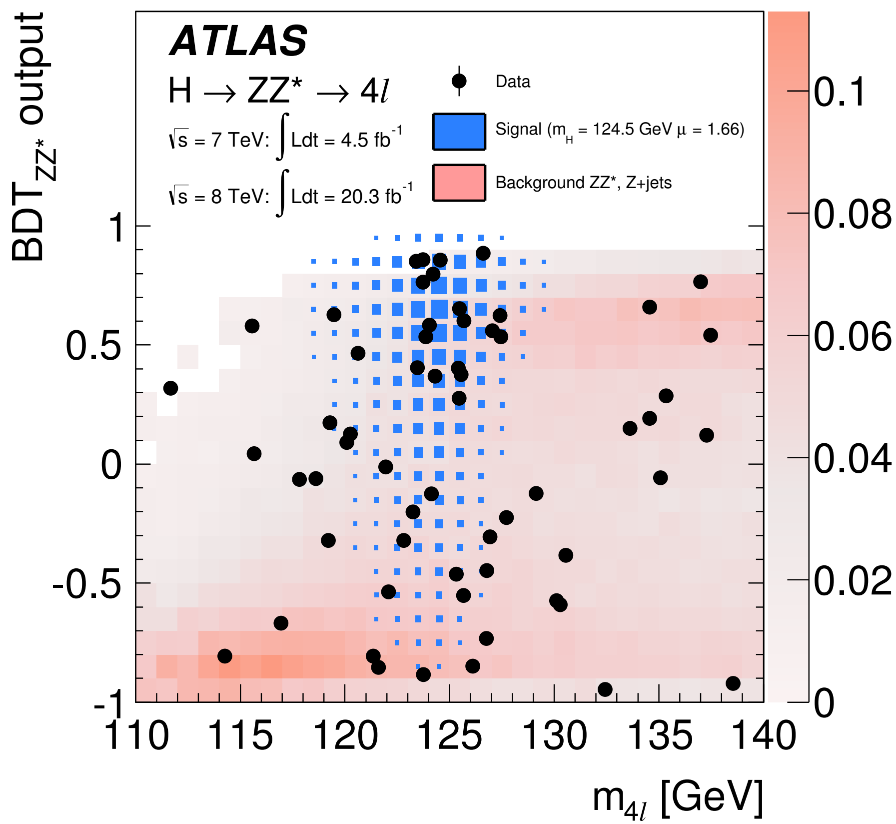
- Discriminant = likelihood ratio e.g.

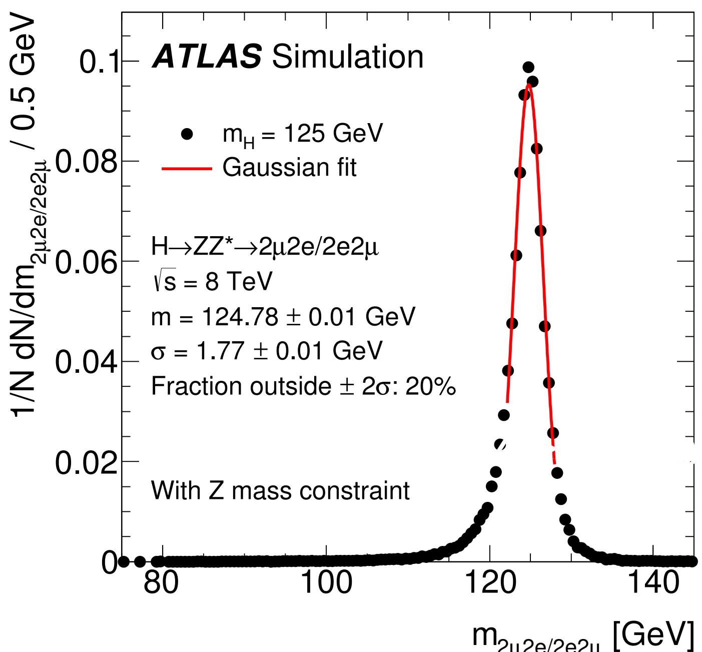
$$\mathcal{D}^{\text{kin}}_{\text{bkg}} = \frac{\mathcal{P}^{\text{kin}}_{0^+}}{\mathcal{P}^{\text{kin}}_{0^+} + \mathcal{P}^{\text{kin}}_{\text{bkg}}}$$

Phys. Rev. D 91, 012006 (2015)

Mass measurement

- **BDT discriminant** using LO matrix element discriminant, η and p_T of 4l-system
- FSR photon recovery
- Using **Z-mass constrained kinematic fit** on leading di-lepton mass with 15% improvement in resolution





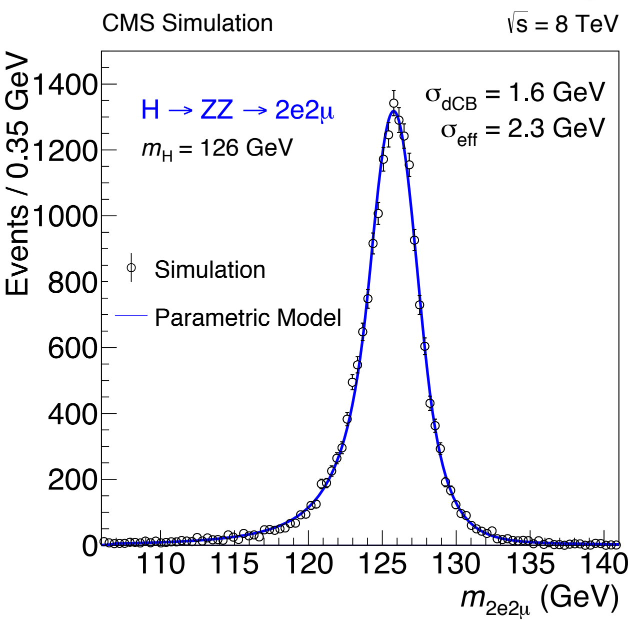
- **2D fit to (BDT, m_{4l})** distribution to extract m_H
- **8% improvement in mass precision from using 2D fit**

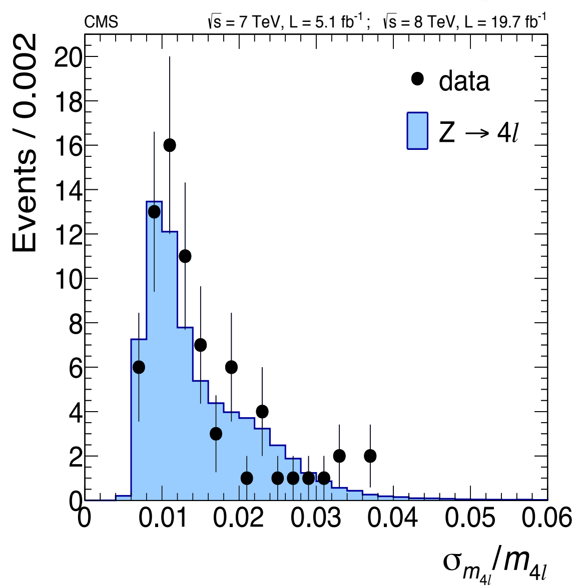
Phys. Rev. D 89, 092007 (2014)

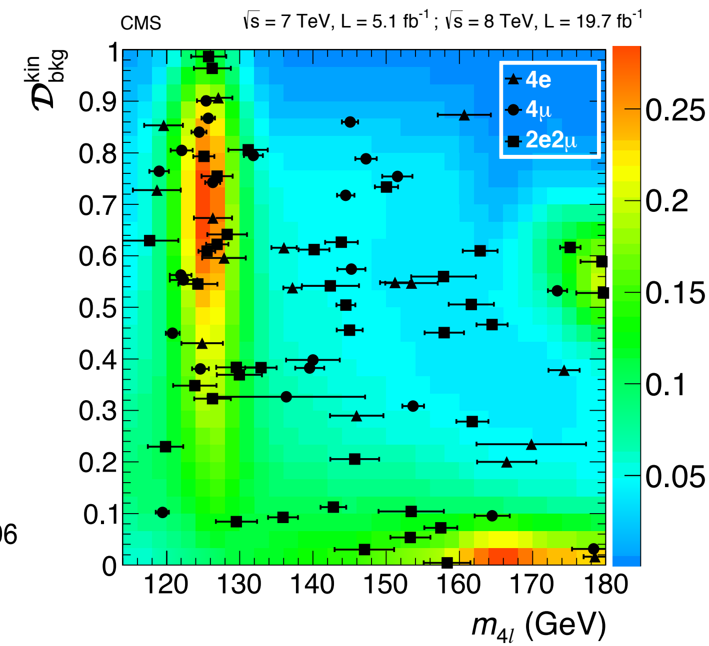
Mass measurement

- **Kinematic discriminant**
- **3D fit** to distribution of m_{4l}, D^{kin}_{bkg} and **per-event mass resolution D_m (8% expected gain in precision)**

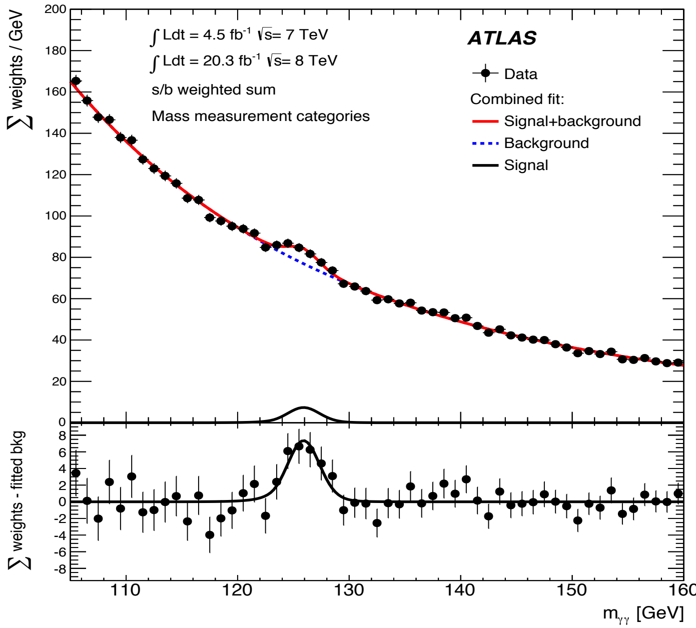
$$\mathcal{L}^{m,\Gamma}_{3D} \equiv \mathcal{L}^{m,\Gamma}_{3D}(m_{4\ell}, \mathcal{D}_{\rm m}, \mathcal{D}^{\rm kin}_{\rm bkg}) = \mathcal{P}(m_{4\ell}|m_{\rm H}, \Gamma, \mathcal{D}_{\rm m})\mathcal{P}(\mathcal{D}_{\rm m}|m_{4\ell}) \times \mathcal{P}(\mathcal{D}^{\rm kin}_{\rm bkg}|m_{4\ell})$$



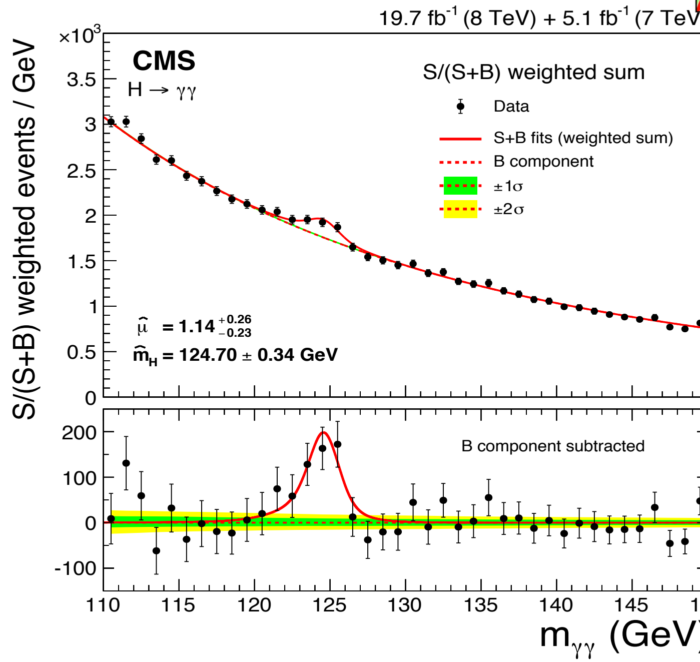




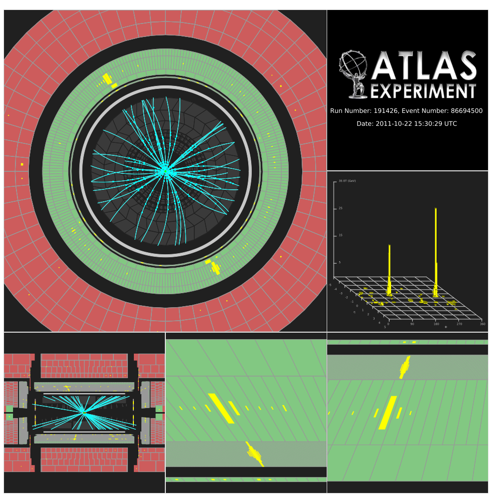
H->γγ channel

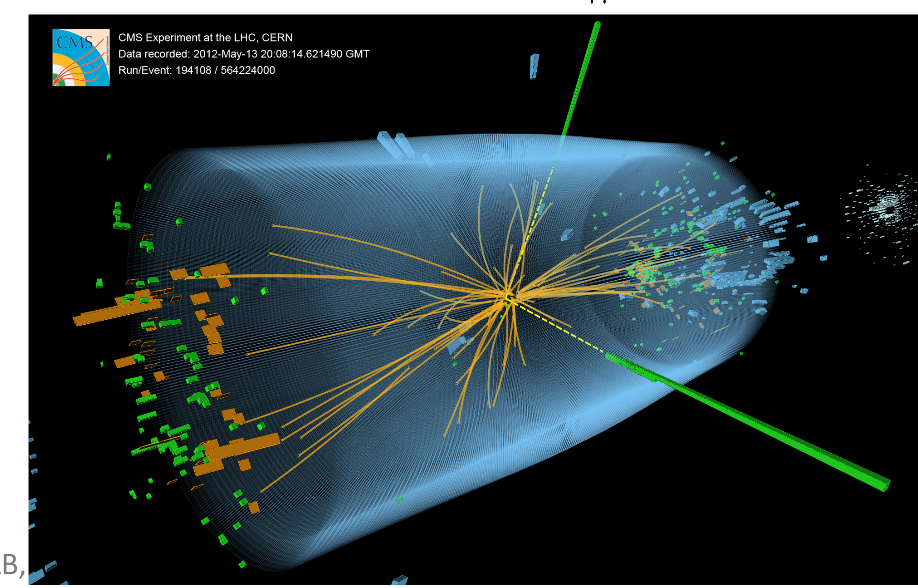


Phys. Rev. D 90, 052004 (2014)



Eur. Phys. J. C 74 (2014) 3076

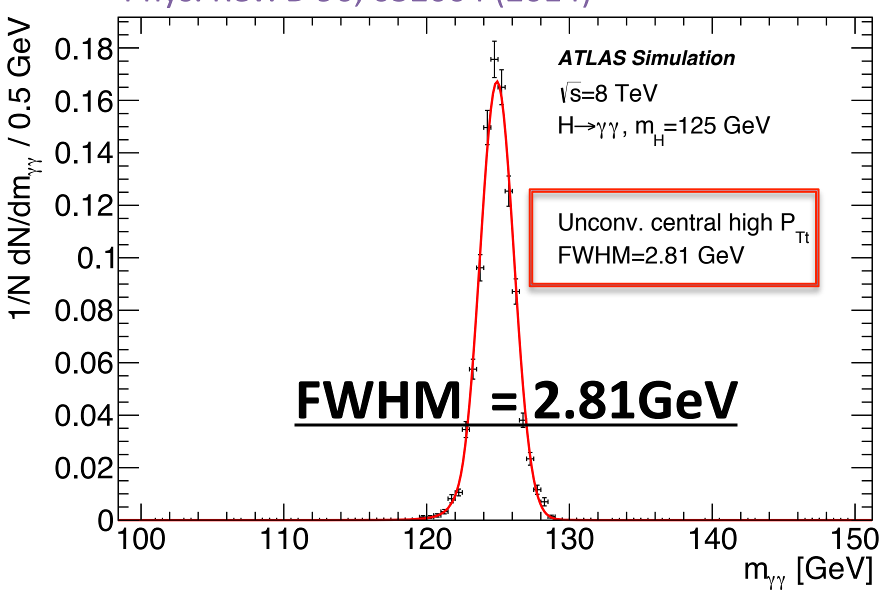




Analysis

- **ATLAS**
  - **Dedicated analysis optimized for mass measurement**
  - **10 event categories** with different S/B and mass resolution (based on unconverted/converted photon; |η| of photon; d- photon momentum transverse to thrust)
  - Neural network using photon pointing + tracks + recoil info to select most probable primary vertex

Phys. Rev. D 90, 052004 (2014)



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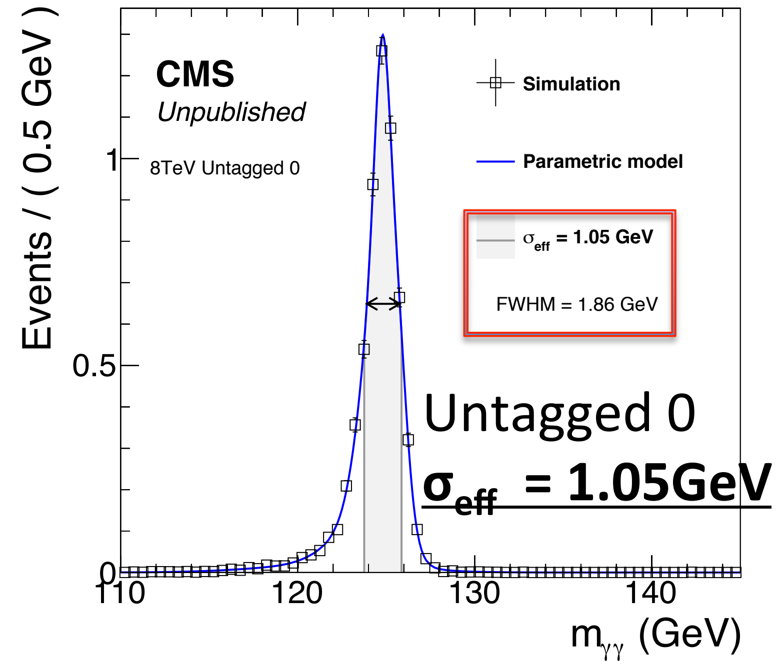
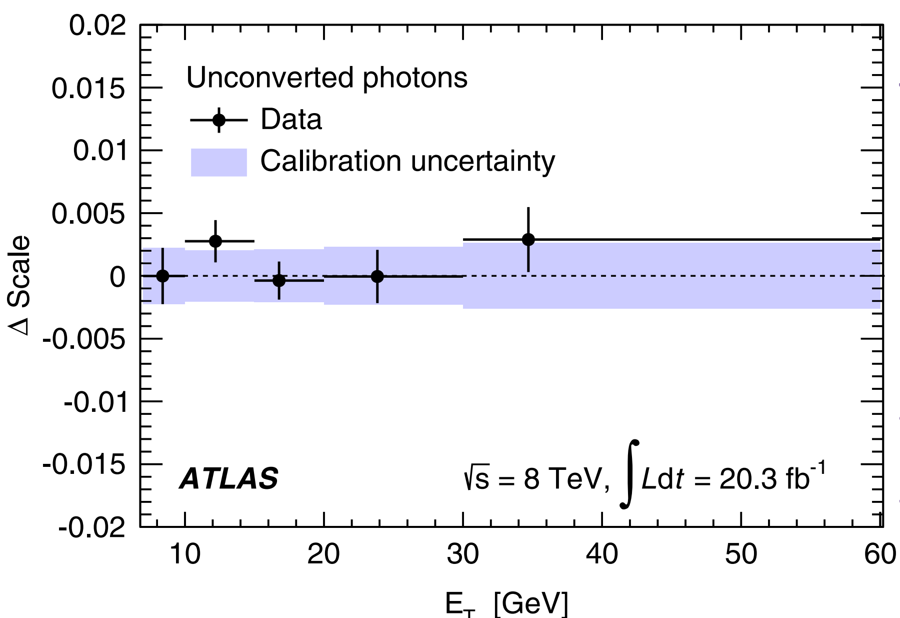


- **CMS**
  - Events are **tagged by production mode**
  - **Untagged events are further classified** according to an MVA (BDT) based on mass resolution, photon kinematics, photon quality (shower shape, isolation)
  - Vertex selected using BDT trained with tracks + recoil info + photon pointing (converted photons)

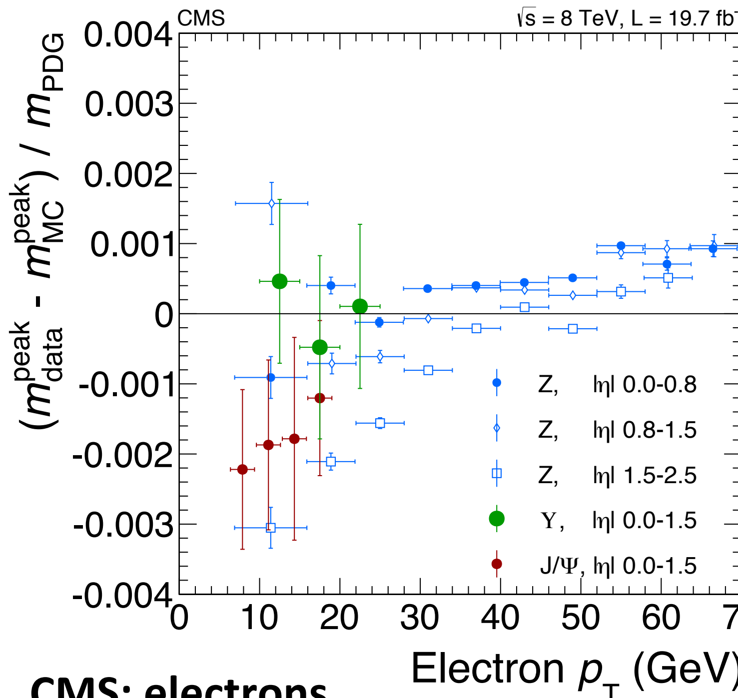
Lepton and photon p_T scales

- **ECAL energy**: corrections from simulations; residual corrections from data/MC comparison of reconstructed Z->e^+e^- mass
- **Muon scale** calibrated using Z, J/ψ and Υ masses
- Lepton scale validated using Z, J/ψ and Υ decay leptons
- Validation of photon calibration with Z->μμγ FSR photons

Examples of response linearity checks



Phys. Rev. D 90, 052004 (2014)



Phys. Rev. D 89, 092007 (2014)

ATLAS; photons

Relative difference bw/ nominal scale from Z->ee and measured scale in Z->μμγ

CMS; electrons

Resulting systematic uncertainty on m_{4l} peak: 0.3% (~40 MeV) in 4e and 0.1% in 2e2mu

Combination of H mass measurements

- H boson mass determined by fitting the m_H-dependent distributions to the data by maximizing the **profiled likelihood ratio**

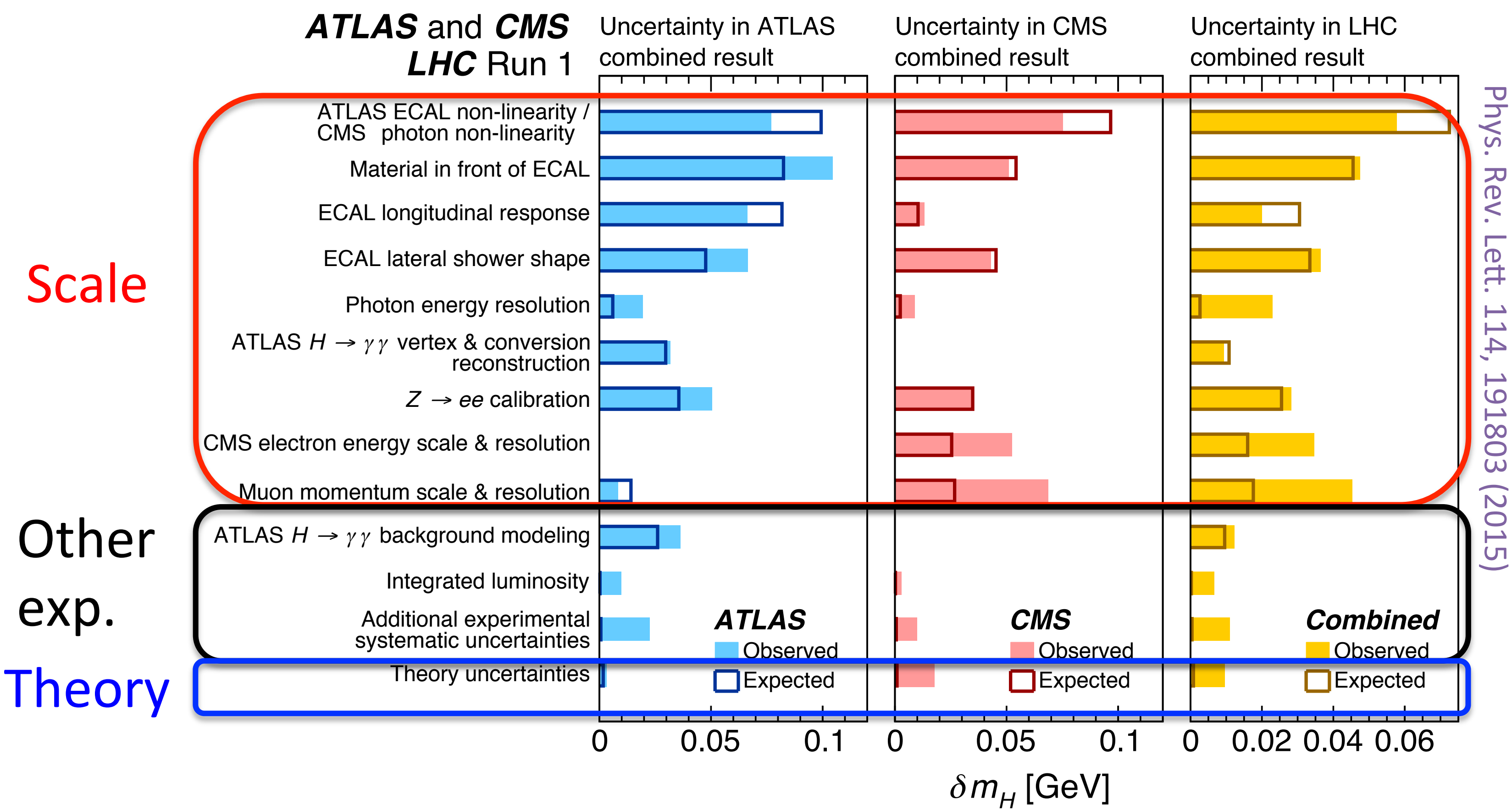
$$\Lambda(m_H) = \frac{L(m_H\,,\,\hat{\hat{\mu}}^{\gamma\gamma}_{ggF+t\bar{t}H}(m_H)\,,\,\hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}(m_H)\,,\,\hat{\hat{\mu}}^{4\ell}(m_H)\,,\,\hat{\hat{\theta}}(m_H))}{L(\hat{m}_H,\hat{\mu}^{\gamma\gamma}_{ggF+t\bar{t}H},\hat{\mu}^{\gamma\gamma}_{VBF+VH},\hat{\mu}^{4\ell},\hat{\theta})}$$

- **m_H**: parameter of interest
- **Three signal strengths $\mu = \sigma/\sigma_{SM}(m_H)$** to reduce model-dependence
  - **$\mu^{\gamma\gamma}_{ggF+ttH}$** : scaling for gluon fusion an ttH production for γγ channel
  - **$\mu^{\gamma\gamma}_{VBF+VH}$** : VBF and associated production for γγ channel
  - **μ^{4l}** : 4l channel
  - assumed to be equal between ATLAS and CMS for nominal result
- **Θ** : nuisance parameters (systematic uncertainties)

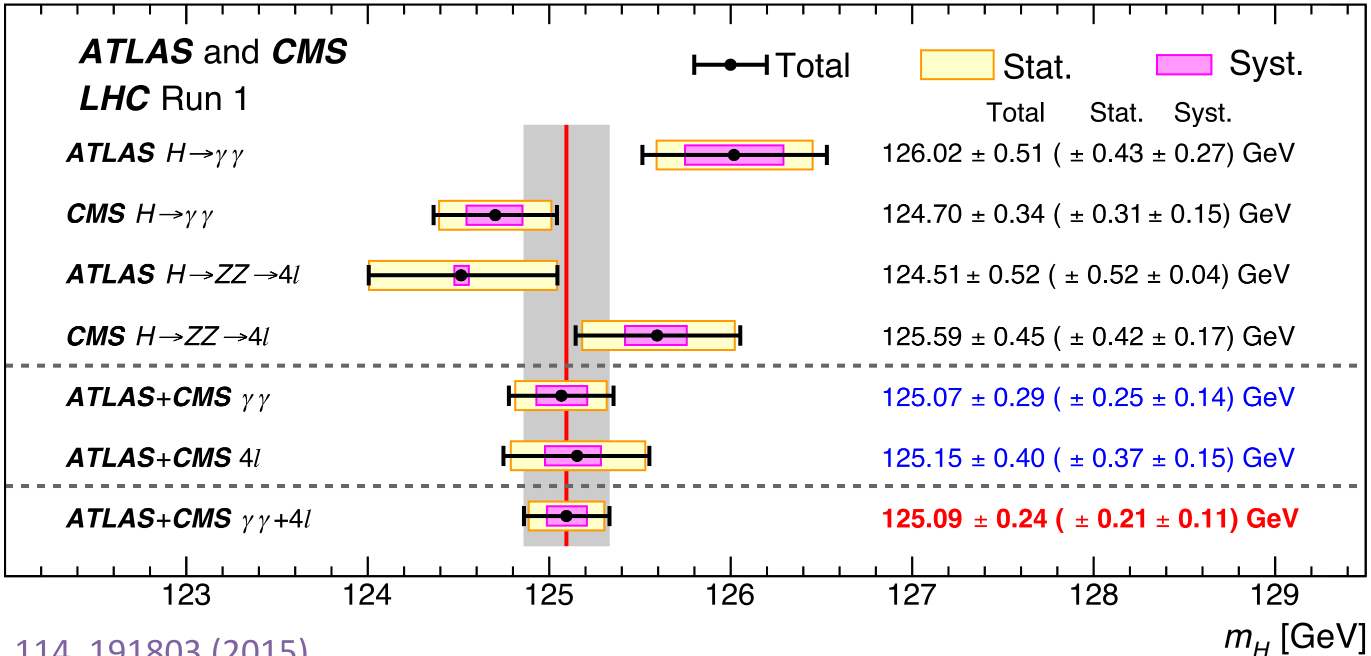
Systematic uncertainties

The mass shift δm_H :

difference in m_H when re-maximizing the profile-likelihood ratio after **fixing the nuisance parameter in question to its best-fit value varied by +/-1σ**



Combined H mass



Phys. Rev. Lett. 114, 191803 (2015)

m_H = 125.09 ± 0.21(stat.) ± 0.11(scale) ± 0.02(other) ± 0.01(theory) GeV

- **stat. uncertainty dominates** (computed by profiling signal strengths and background model parameters)
- **scale uncertainty is the largest systematic uncertainty**
- **theory uncertainty is small** but interference effects have been neglected

Compatibility tests

- **Tension between experiments** per channel

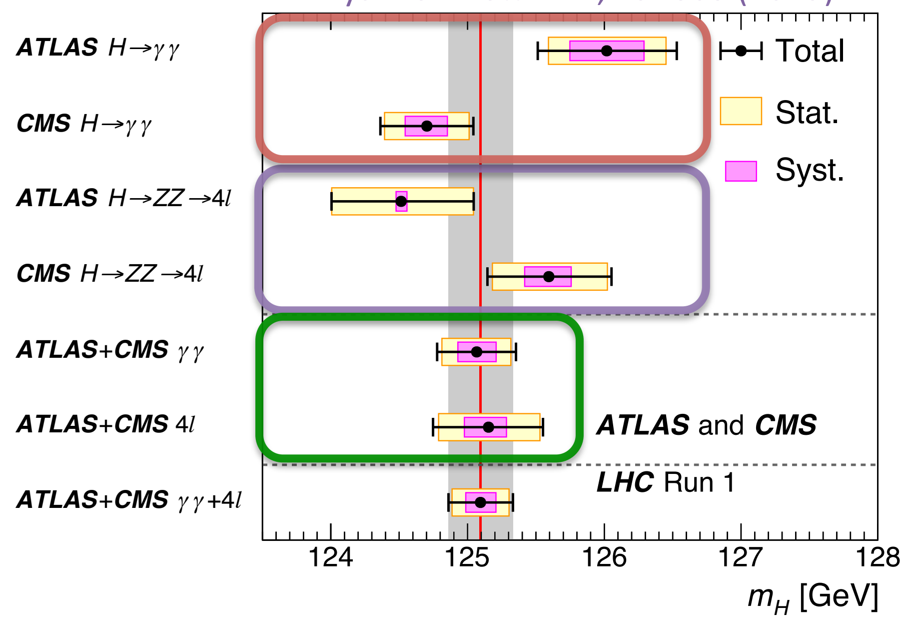
  $m_{\gamma\gamma}$ (ATLAS) - $m_{\gamma\gamma}$ (CMS) = 1.3 ± 0.6 GeV
  2.1σ

  m_{4l} (ATLAS) - m_{4l} (CMS) = - 0.9 ± 0.7 GeV
  1.3σ

- **Tension between γγ and 4l channels**

  $m_{\gamma\gamma}$ (ATLAS+CMS) - m_{4l} (ATLAS+CMS)
  = - 0.1 ± 0.5 GeV
  No tension

Phys. Rev. Lett. 114, 191803 (2015)



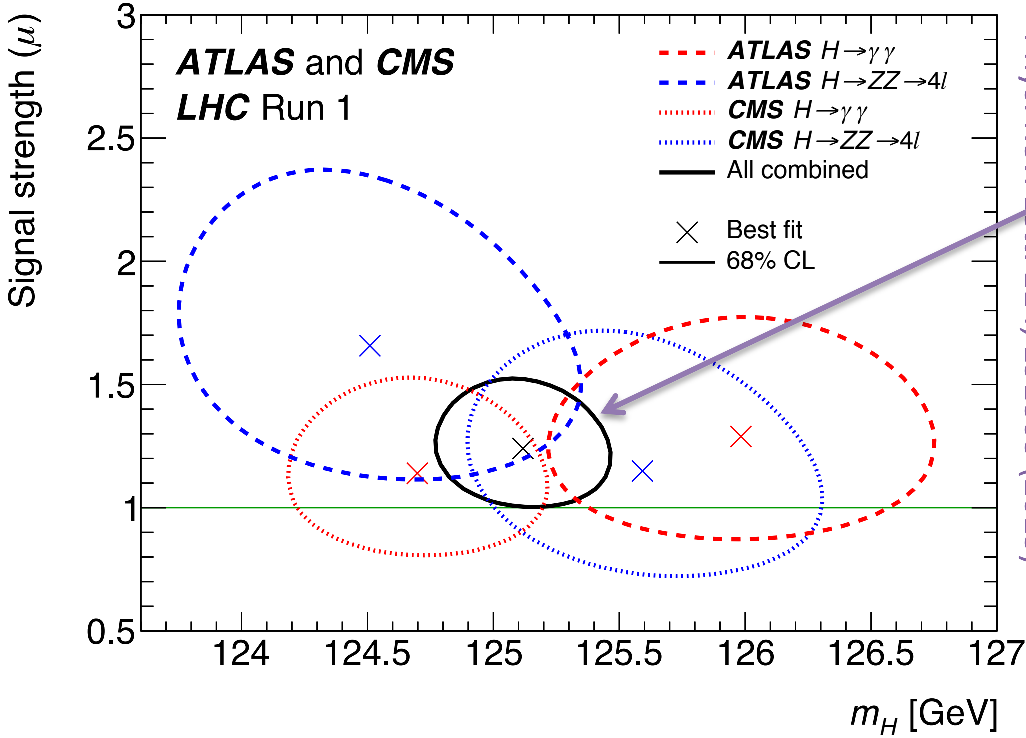
- **Test of 1 common mass vs. 4 masses ($\Delta\chi^2$ with 3 degrees of freedom)**
  - p-value: 10%
  - 7% if allowing different signal strengths in ATLAS and CMS

Correlation of m_H and signal strengths

- **Signal strengths from nominal fit:**

  $\mu^{\gamma\gamma}_{ggF+ttH} = 1.15^{+0.28}_{-0.25}$ // $\mu^{\gamma\gamma}_{VBF+VH} = 1.17^{+0.58}_{-0.53}$ // $\mu^{4l} = 1.40^{+0.30}_{-0.25}$

(i) Allowing the **ATLAS and CMS signal strengths to vary independently** yields a result with **40MeV higher in m_H**



Phys. Rev. Lett. 114, 191803 (2015)

(ii) Single-signal strength fit
$\mu = \mu^{\gamma\gamma}_{ggF+ttH} = \mu^{\gamma\gamma}_{VBF+VH} = \mu^{4l}$

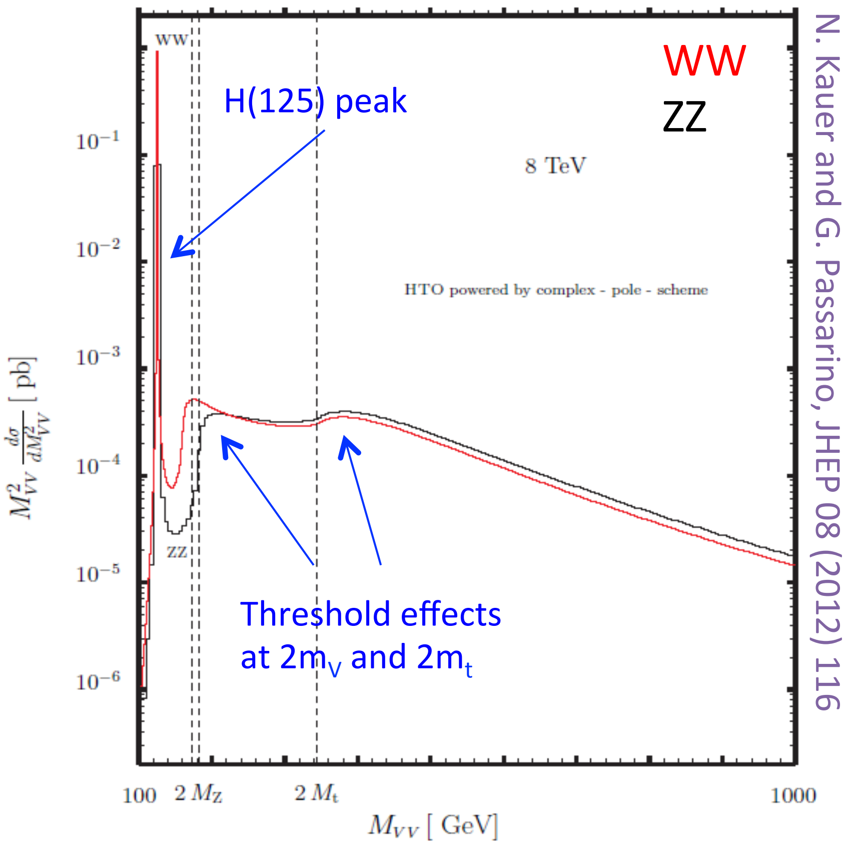
(iii) Assuming **all signal strengths = 1** yields a **70MeV higher mass**, mainly due to rapid variation of H->ZZ branching fraction with m_H

Offshell H decays

Offshell decays and H width

Non-negligible **offshell contribution** to H(*) ⟶ VV cross section (V = W, Z)

gluon-gluon fusion production



$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}$$

Offshell signal strength μ^{off} sensitive to modification in couplings:

$$\mu_{\text{off-shell}}(\hat{s}) = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$$

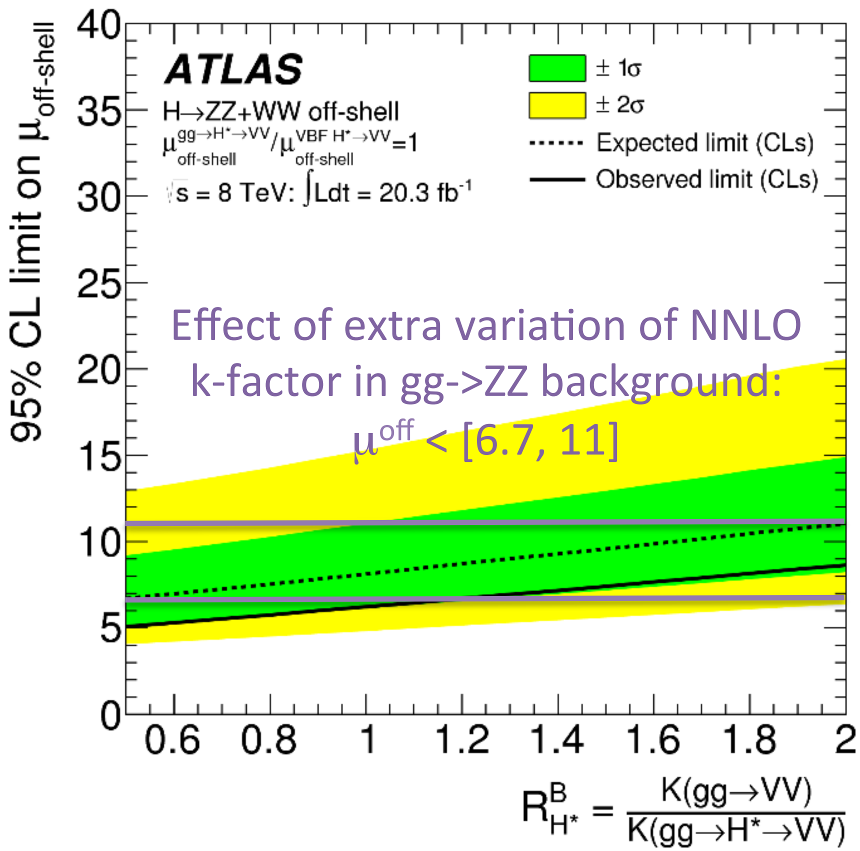
$\mu^{\text{off}}/\mu^{\text{on}}$ can be interpreted as Γ_H/Γ_{SM} if couplings depend on m_{ZZ} as in SM:

$$\mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

Eur. Phys. J. C (2015) 75:335

ATLAS analysis

Search in $ZZ \rightarrow \ell\ell\ell\ell$, $ZZ \rightarrow \ell\ell\nu\nu$ and $WW \rightarrow e\mu\nu\nu$ final states, inclusive in jet multiplicity



Limits on $\mu^{offshell}$ at 95% CL

1) Assuming μ^{off}_{ggF} and μ^{off}_{VBF} are equal

μ^{off} < 6.2 observed (8.1 expected)

2) Assuming μ^{off}_{VBF} = 1 (SM in VBF)

μ^{off}_{ggF} < 6.7 obs. (9.1 exp.)

Limit on Γ_H assuming same on-shell and off-shell coupling scale factors

Obs. (exp.) 95% CL limit:

$\Gamma_H/\Gamma_{SM} < 5.5\ (8.0)$

equivalent to

$\Gamma_H < 23\ (33)$ MeV

Limit on change in ggF coupling assuming no change in VBF

$R_{gg} = \kappa_{g,\,off\text{-}shell} / \kappa_{g,\,on\text{-}shell} < 6.0$

CMS analysis

Baseline analysis 4ℓ and 2ℓ2ν channels (dijet category in onshell region)

Observed (expected) 95% CL limit:

Γ_H/Γ_{SM} < 5.4 (8.0)

Best fit value:

$\Gamma_H/\Gamma_{SM} = 0.4^{+1.8}_{-0.4}$

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Γ_H < 22 (33) MeV

$\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV

$\mu_{ggF} = 0.81^{+0.47}_{-0.37}$

$\mu_{VBF} = 1.7^{+2.2}_{-1.7}$

Compatible with SM

arXiv:1507.06656

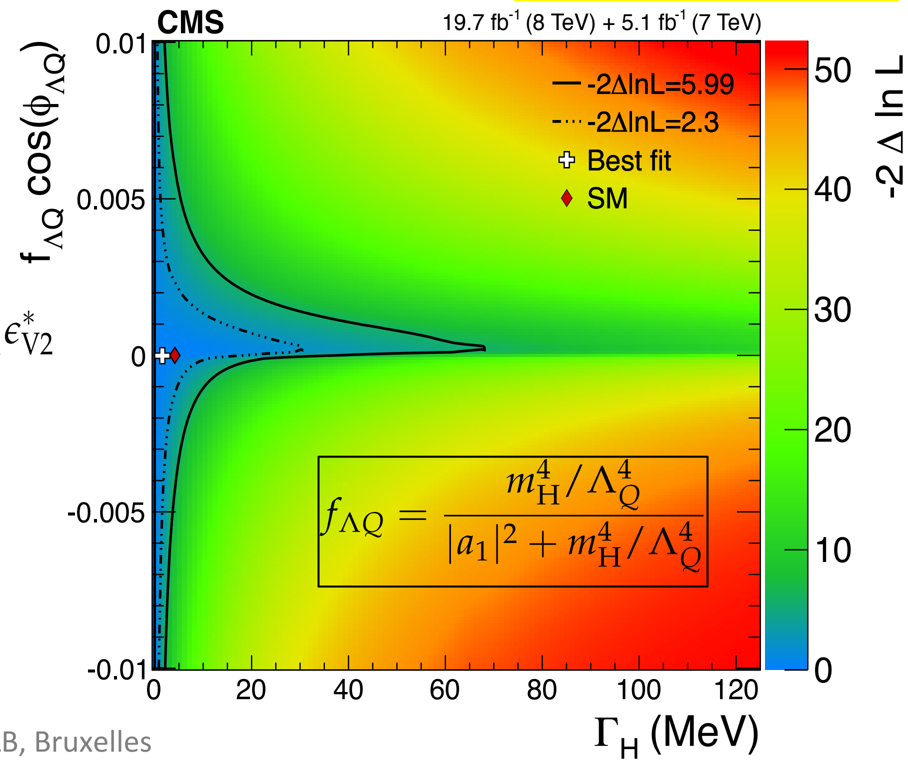
Updated analysis (H->ZZ->4ℓ only)

- Dijet category added in offshell region
- Allows to search for mass-dependent HVV anomalous coupling Λ_Q

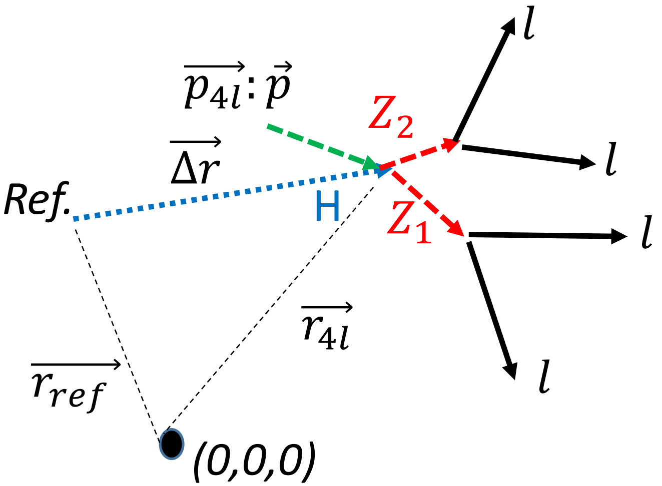
$$A(\mathrm{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$

$$+ a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- 2D limit on Γ_H and effective anomalous cross section fraction $f_{\Lambda Q}$



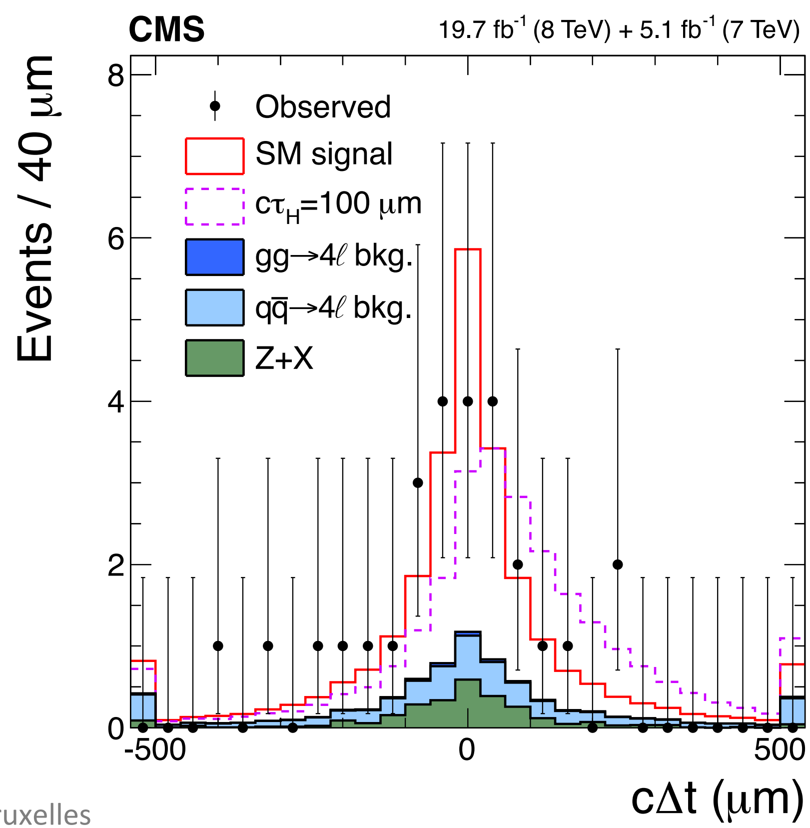
Lifetime analysis



- In SM, $c\tau^{SM}_H = 4.8 \times 10^{-8}$ μm; well beyond experimental precision
- Search for displaced H->ZZ->4l decay vertex
  - Event selection updated to be unbiased wrt. lifetime
  - p_T-spectrum dependence of vertex resolution taken into account

$$\Delta t \equiv \frac{m_{4l}}{p_T}\left(\overrightarrow{\Delta r_{\perp}}.\widehat{p_T}\right)$$

$$< \Delta t > = \tau_H = \frac{\hbar}{\Gamma_H}$$



Observed 95% CL limit:

$c\tau_H < 57$ μm; $\Gamma > 3.5\ 10^{-9}$ MeV

First direct experimental limit on H boson lifetime

Heavy scalar searches in ZZ and WW final states

Recent results

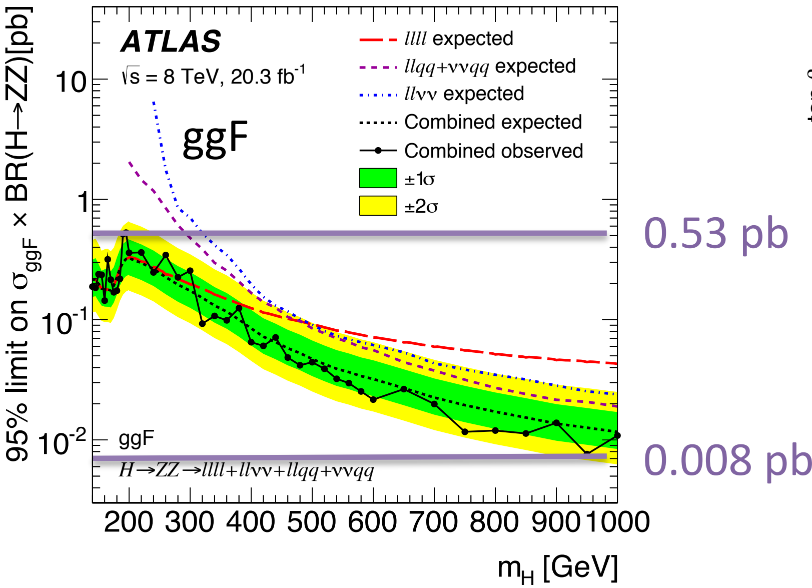
H->ZZ analysis

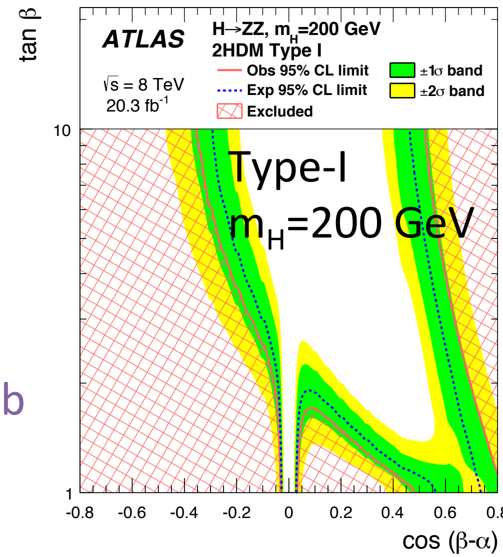
- Additional scalar searched for in [140, 1000] GeV mass range
- Search performed in the $ZZ \rightarrow \ell\ell\ell\ell$, $ZZ \rightarrow \ell\ell\nu\nu$, $ZZ \rightarrow \ell\ell qq$ and $ZZ \rightarrow \nu\nu qq$ final states
- Three models considered:
  - Narrow-width heavy scalar
    - Limits on σ_{ggF}xBR(H->ZZ) and σ_{VBF}xBR(H->ZZ)
  - Type-I and Type-II 2HDM models
    - Limits on m_H, tan(β) and coupling to Z bosons cos(β-α)

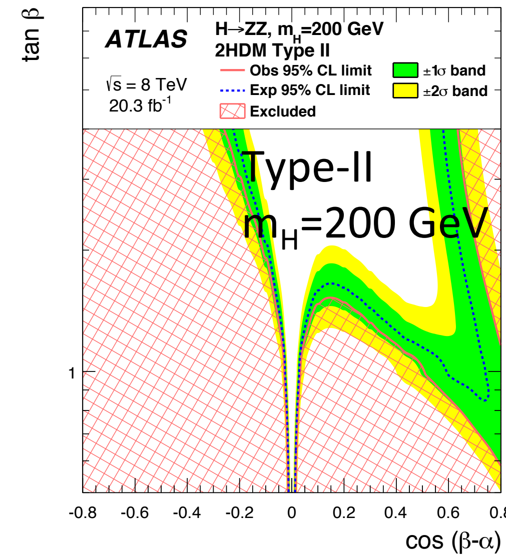
arXiv:1507.05930

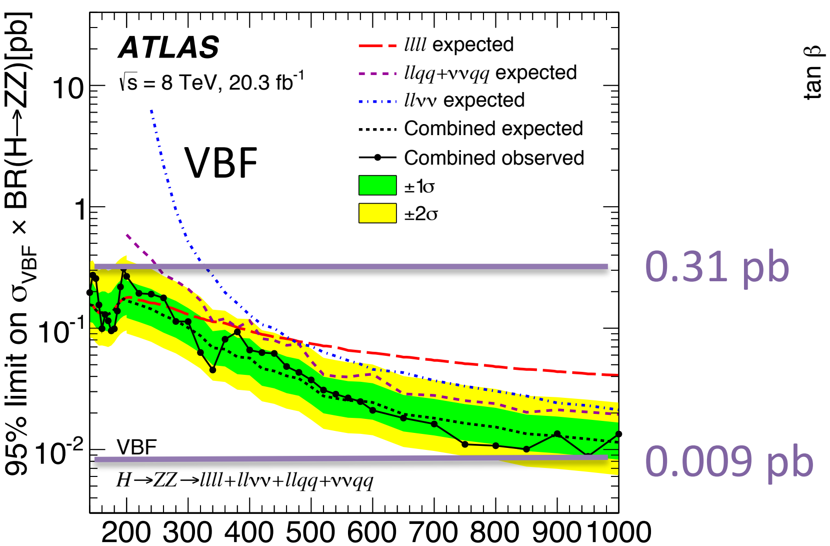
Results

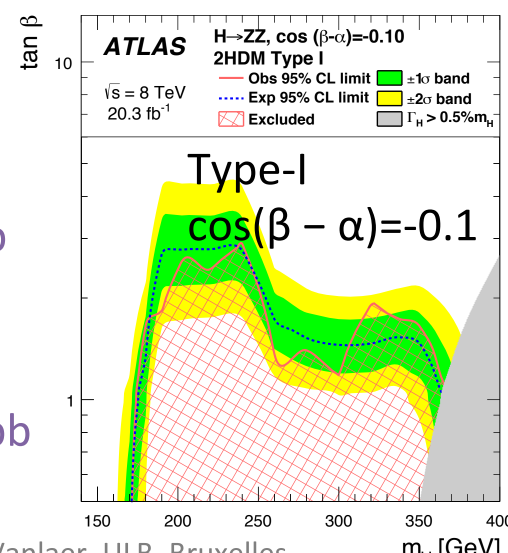
More stringent limits set compared to indirect constraints from h(125 GeV)->ZZ in relevant range of parameters

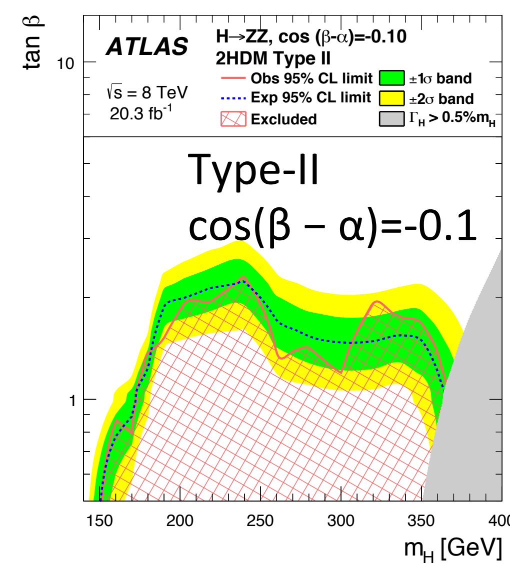












H->ZZ+WW analysis

- In [140, 1000] GeV mass range
- Search in WW→$\ell\nu\ell\nu$, WW→$\ell\nu$jj, WW→$\ell\nu$J, ZZ→$\ell\ell\ell\ell$, ZZ→$\ell\ell\tau\tau$, ZZ→$\ell\ell\nu\nu$, ZZ→$\ell\ell$qq final states
- Several models considered:
  - Heavy scalar with SM couplings
  - Electroweak singlet mixing with light scalar
    - Couplings of h and H states are universally rescaled by C and C', constrained by unitarity and h(125) signal strength

$$C^2 + C'^2 = 1$$

    - Heavy H is allowed to decay into new modes with a B.F. B_{new}:

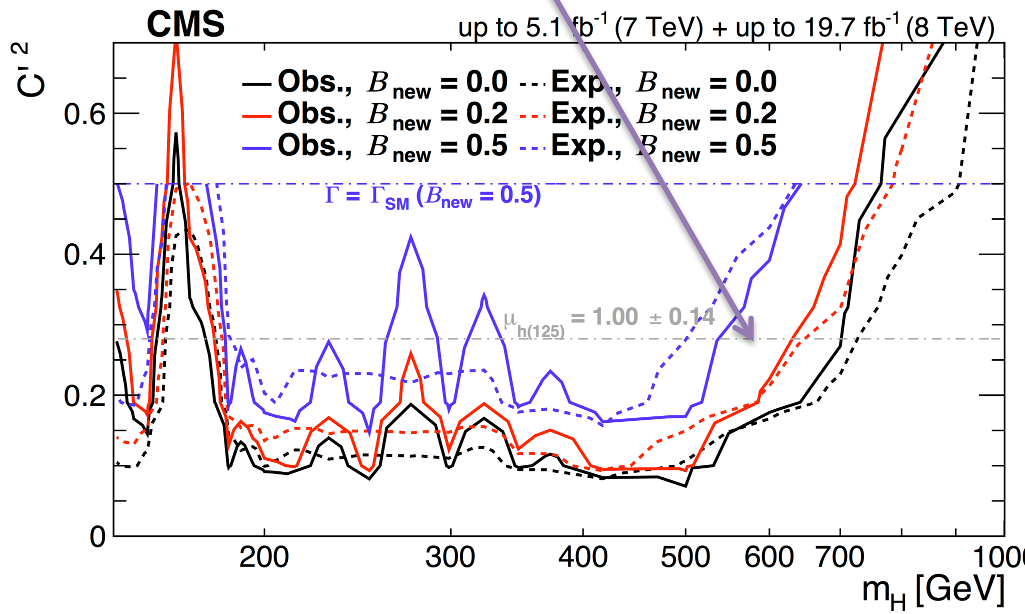
$$\mu' = C'^2 \left(1 - \mathcal{B}_{\text{new}}\right) \qquad \Gamma' = \Gamma_{\text{SM}} \frac{C'^2}{1 - \mathcal{B}_{\text{new}}}$$

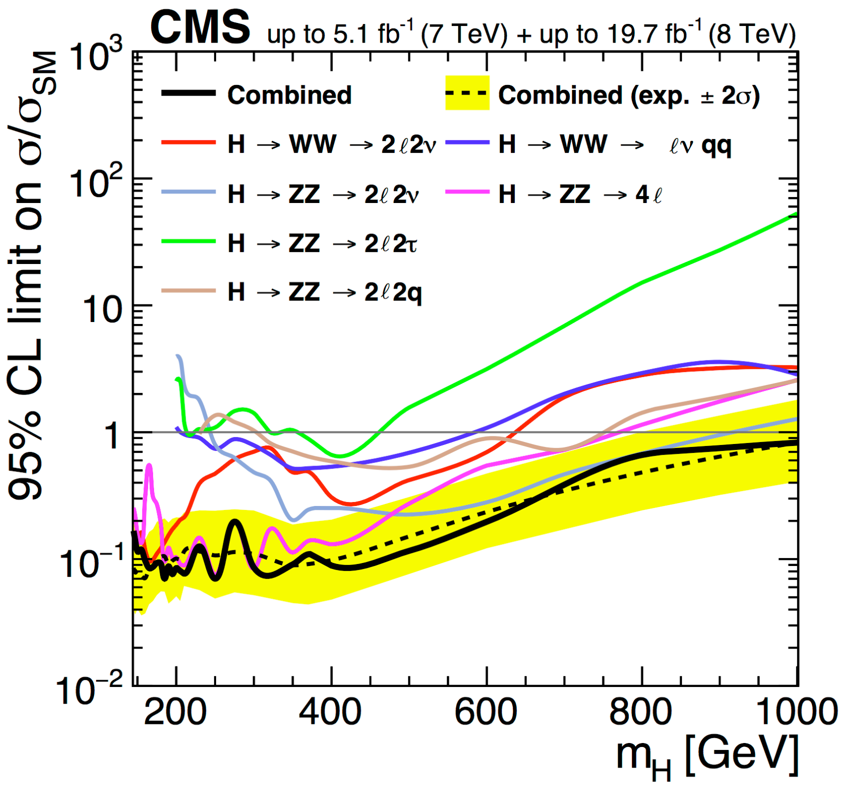
    - Results also interpreted as a generic 2D limit on mass and width

arXiv:1504.00936

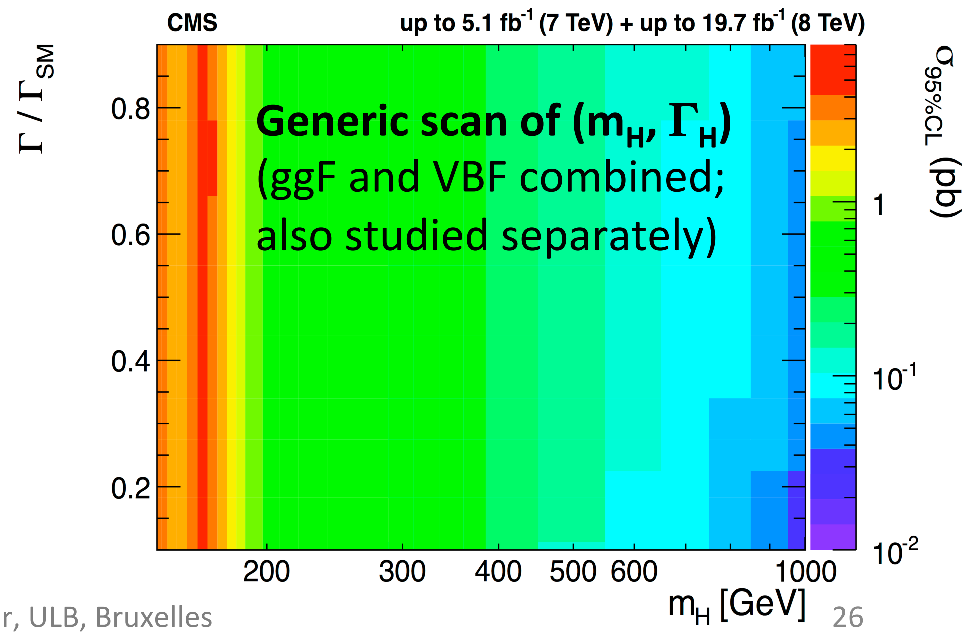
Results

EWK singlet: direct search is competitive with indirect constraint from h(125 GeV)





SM-like scalar: sensitivity down to $0.1 \times \sigma_{SM}$ across a large mass range



Conclusions

- The Run-I ATLAS and CMS combined mass measurement of the H boson is

  m_H = 125.09 ± 0.21(stat.) ± 0.11(scale) GeV

  0.2% precision with Run1 data

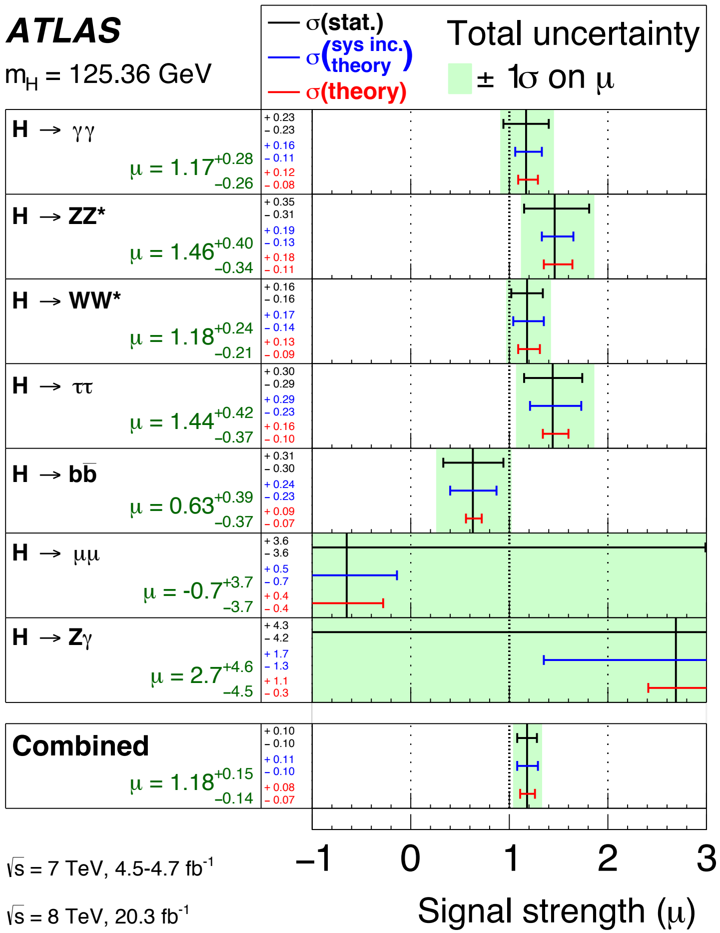
- Offshell decays open interesting perspectives for studying the H boson properties
- Direct searches for massive scalars are competitive with indirect constraints from the study of the H(125) boson
- There is still room for surprises

Back up

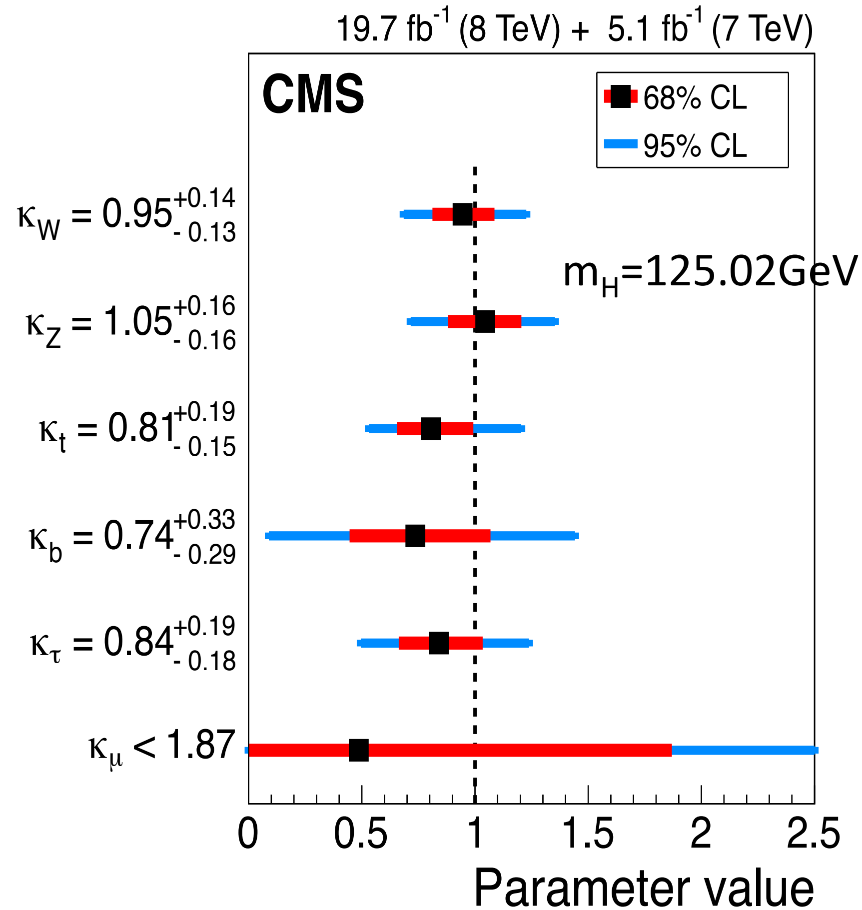
With a combined ATLAS+CMS mass value…

- More combinations can be made

arxiv:1507.04548



Eur. Phys. J. C (2015) 75(212)

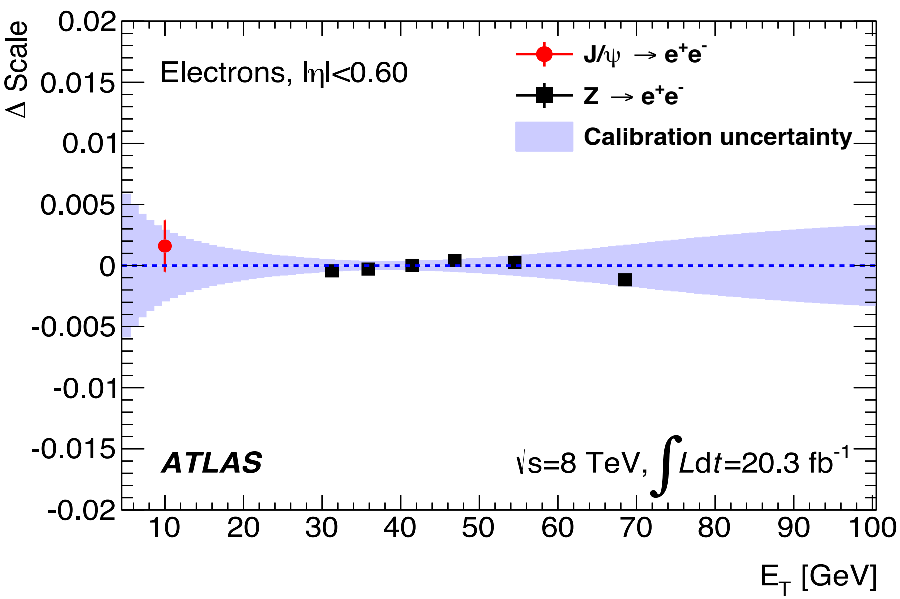


Electron energy scale

- Calibration with Z->ee; extrapolated in kinematic range of H decays
- Validation using also J/Psi and Y->ee
- Linearity of response checked vs electron p_T

ATLAS

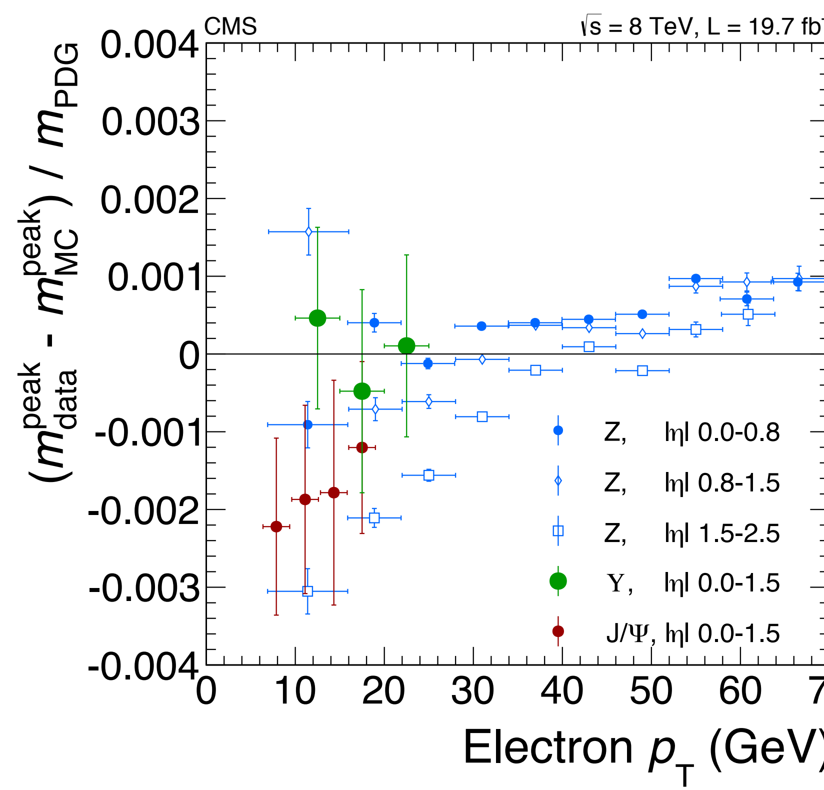
Relative difference bw/ nominal scale at the Z peak and measured scale



Phys. Rev. D 90, 052004 (2014)

CMS

Relative difference bw/ data and simulation after calibration



Phys. Rev. D 89, 092007 (2014)

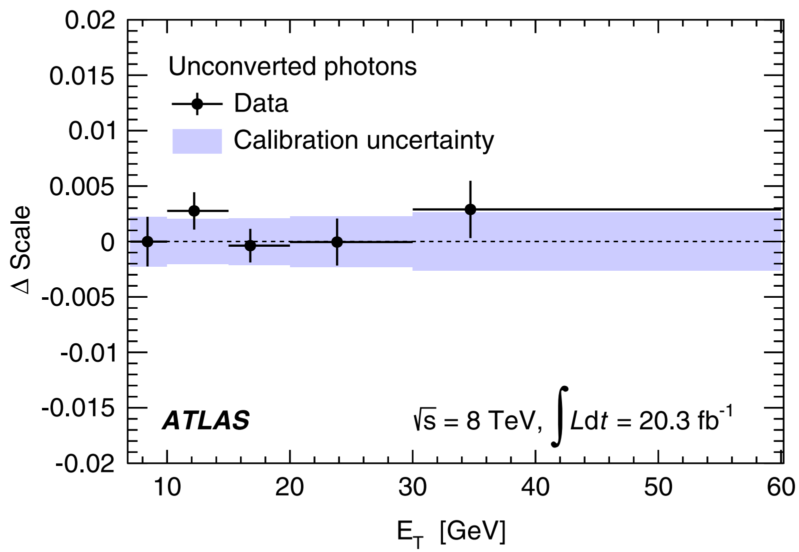
Photon energy scale

- Calibration with Z->ee
- Validation with Z->μμγ

ATLAS

Relative difference bw/ nominal scale at Z->ee peak and measured scale in Z->μμγ

Phys. Rev. D 90, 052004 (2014)

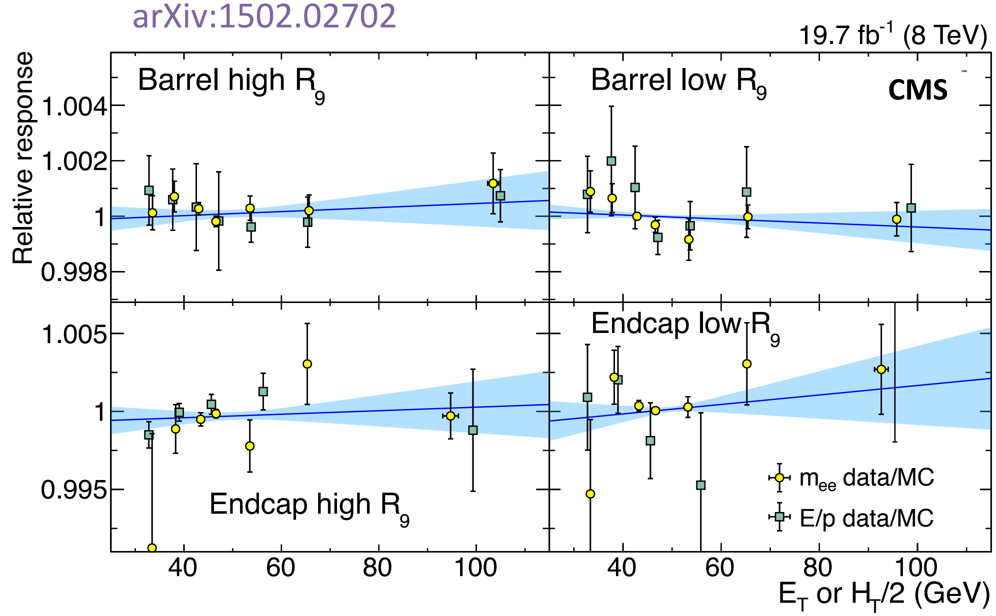


(a)

CMS

Residual discrepancy of the energy response in data relative to that in simulated events as a function of transverse energy (for the *E*/*p* analysis) and of $H_T/2$ (for the dielectron mass analysis) in four *η* and *R*9 categories

arXiv:1502.02702

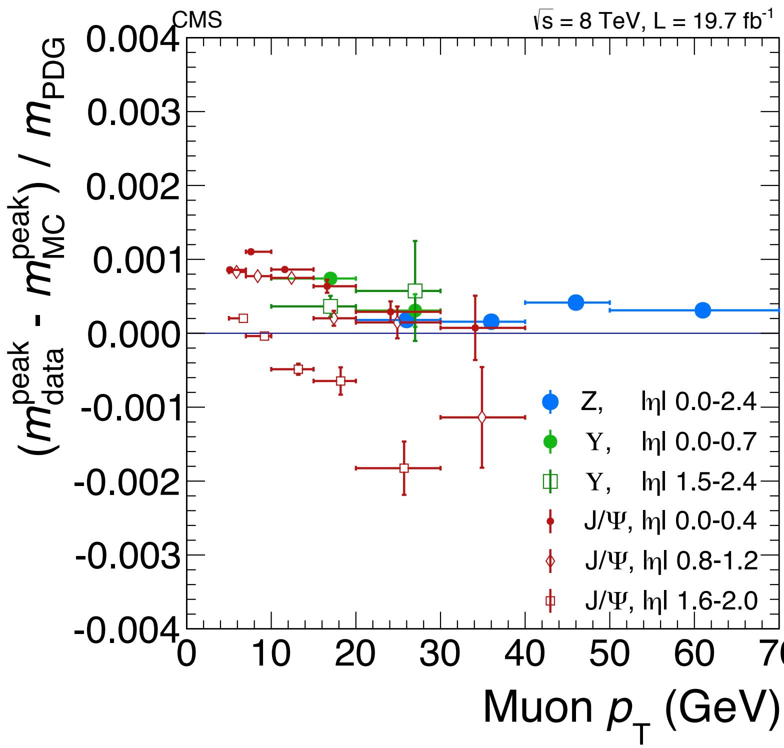


Muon momentum scale

Calibration using Z->μμ, **J/ψ->μμ** and Y->μμ

CMS

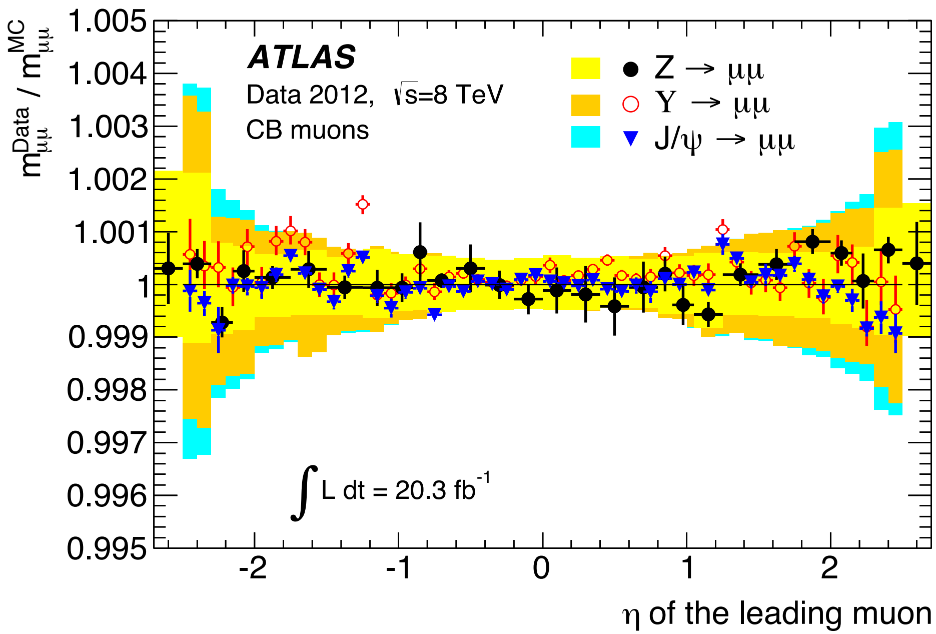
Relative difference of dimuon mass peak bw/ data and simulation after calibration



Phys. Rev. D 89, 092007 (2014)

ATLAS

Ratio of the dimuon mass peak in data and simulation after calibration

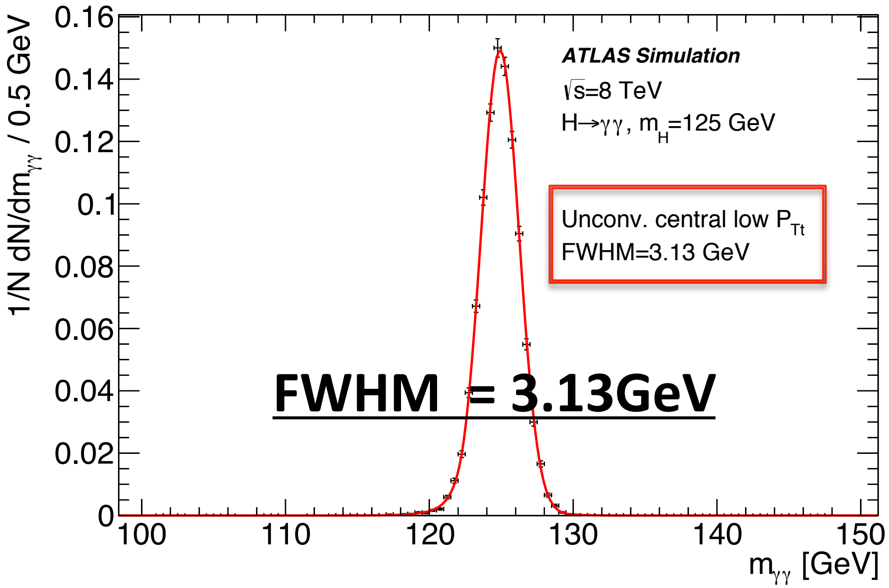


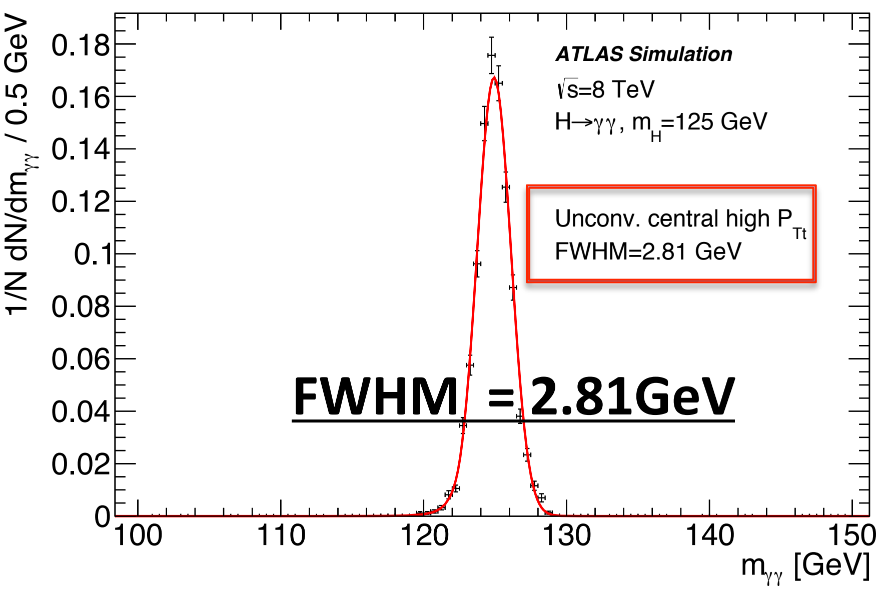
Phys. Rev. D 90, 052004 (2014)

Analysis strategy

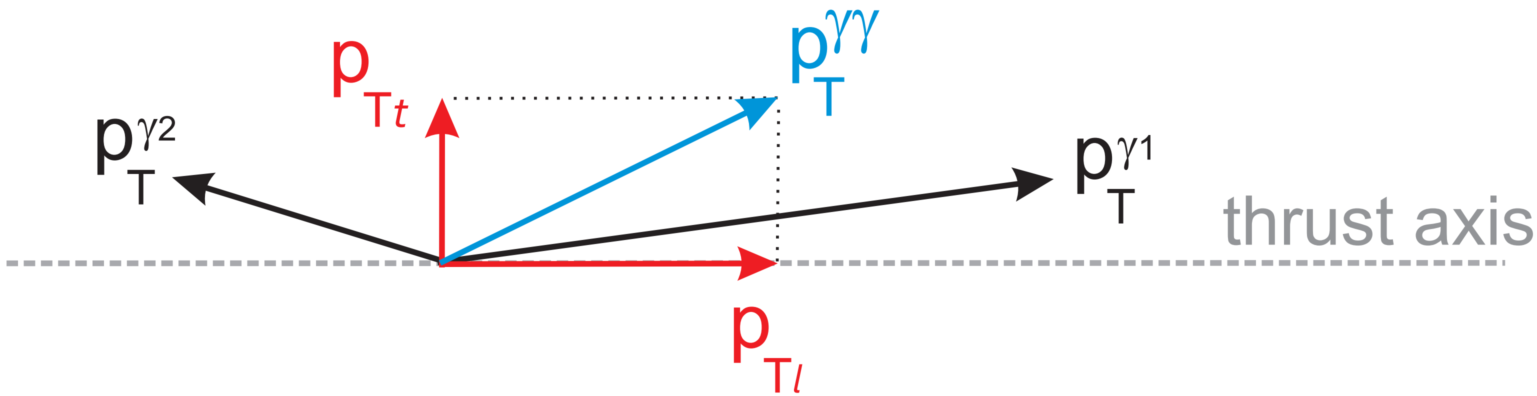
Different categories have **difference S/B, different mass resolutions**

Phys. Rev. D 90, 052004 (2014)



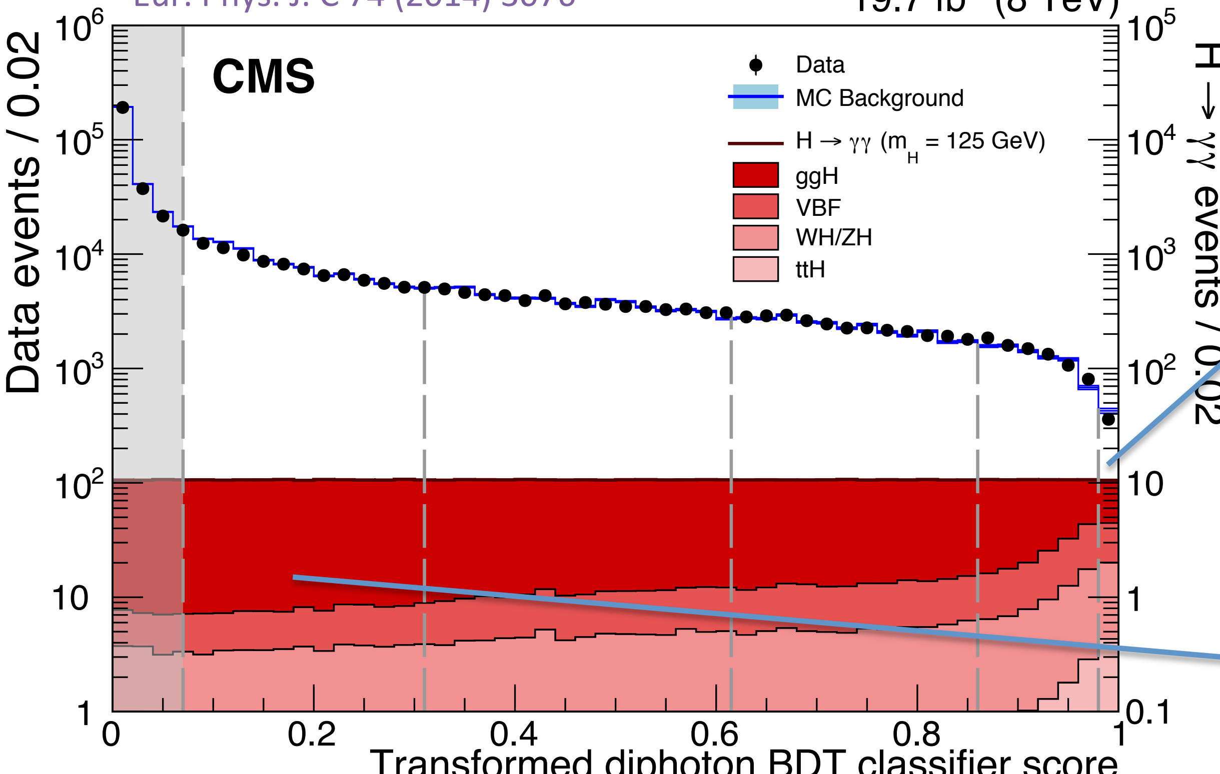


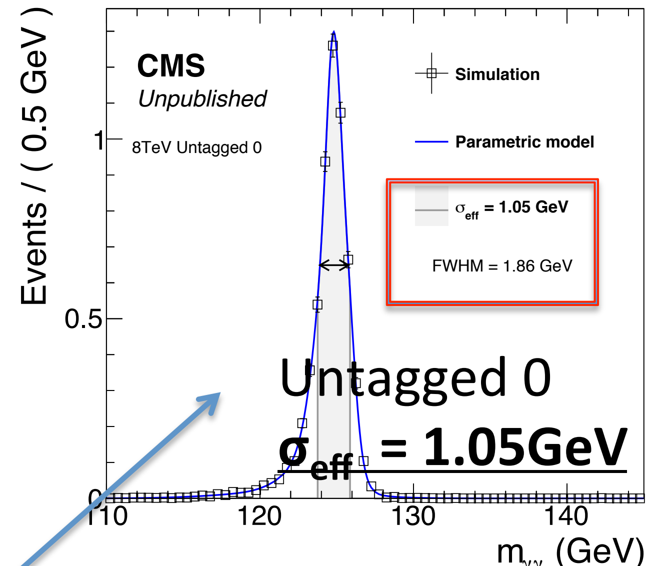
Thrust axis definition

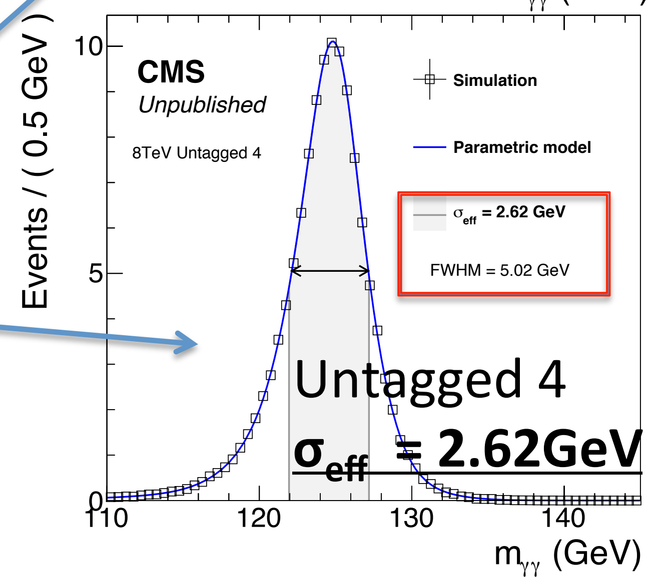


Analysis strategy : BDT classifier

Eur. Phys. J. C 74 (2014) 3076







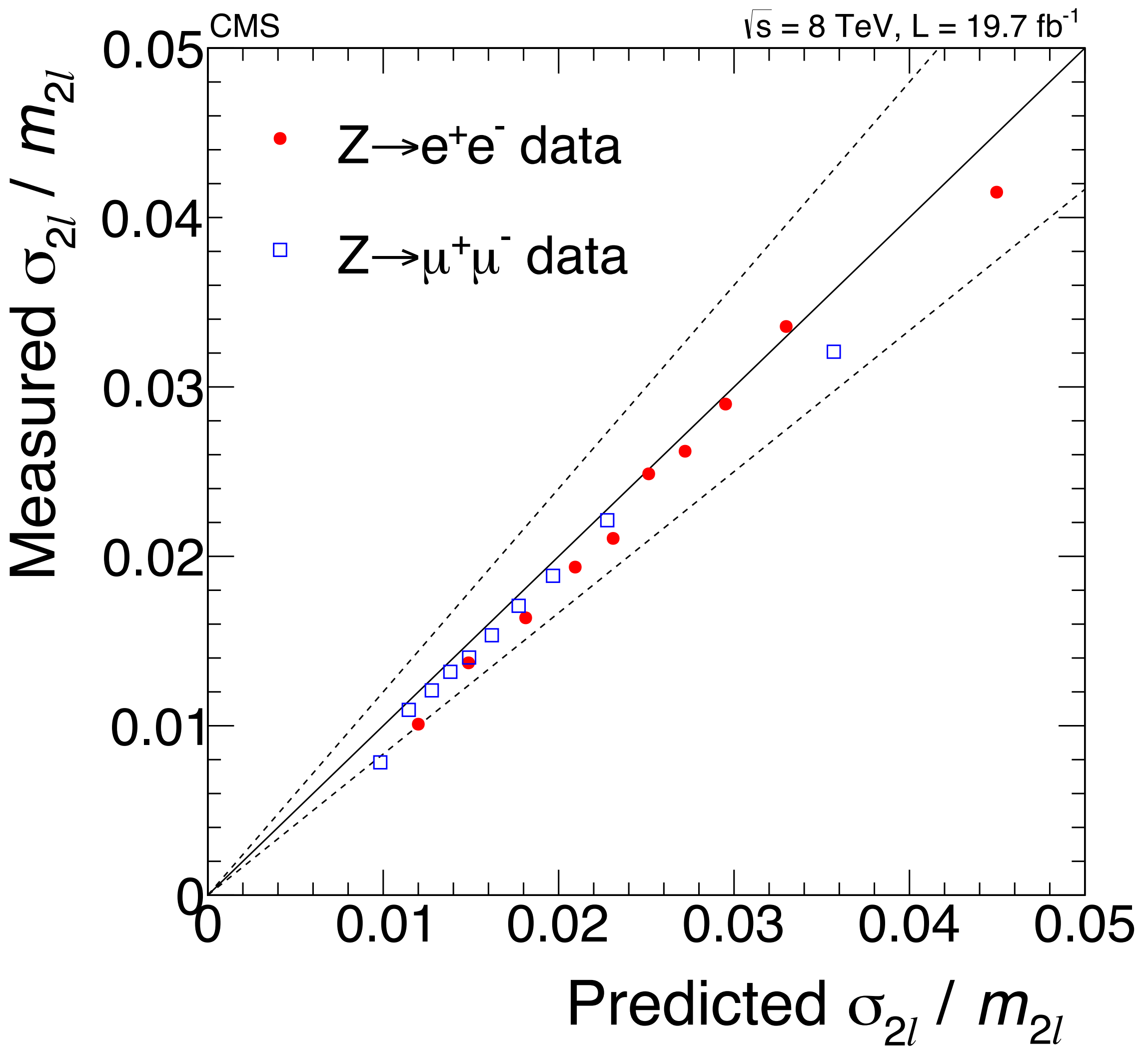
Systematic uncertainties

Phys. Rev. Lett. 114, 191803 (2015)

	Uncertainty in ATLAS combined result [GeV]: observed (expected)	Uncertainty in CMS combined result [GeV]: observed (expected)	Uncertainty in LHC combined result [GeV]: observed (expected)
Scale uncertainties:			
ATLAS ECAL non-linearity / CMS photon non-linearity	0.08 (0.10)	0.08 (0.10)	0.06 (0.07)
Material in front of ECAL	0.10 (0.08)	0.05 (0.05)	0.05 (0.05)
ECAL longitudinal response	0.07 (0.08)	0.01 (0.01)	0.02 (0.03)
ECAL lateral shower shape	0.07 (0.05)	0.04 (0.05)	0.04 (0.03)
Photon energy resolution	0.02 (0.01)	0.01 (<0.01)	0.02 (<0.01)
ATLAS $H \to \gamma\gamma$ vertex & conversion reconstruction	0.03 (0.03)	–	0.01 (0.01)
$Z \to ee$ calibration	0.05 (0.04)	0.03 (0.03)	0.03 (0.03)
CMS electron energy scale & resolution	–	0.05 (0.03)	0.03 (0.02)
Muon momentum scale & resolution	0.01 (0.01)	0.07 (0.03)	0.05 (0.02)
Other uncertainties:			
ATLAS $H \to \gamma\gamma$ background modeling	0.04 (0.03)	–	0.01 (0.01)
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)
Additional experimental systematic uncertainties	0.02 (<0.01)	0.01 (<0.01)	0.01 (<0.01)
Theory uncertainties	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)
Systematic uncertainty (sum in quadrature)	0.18 (0.17)	0.14 (0.13)	0.11 (0.10)
Systematic uncertainty (nominal)	0.18 (0.18)	0.14 (0.13)	0.11 (0.10)
Statistical uncertainty	0.37 (0.37)	0.27 (0.28)	0.21 (0.22)
Total uncertainty	0.41 (0.41)	0.30 (0.31)	0.24 (0.24)
Analysis weights	35% (36%)	65% (64%)	–

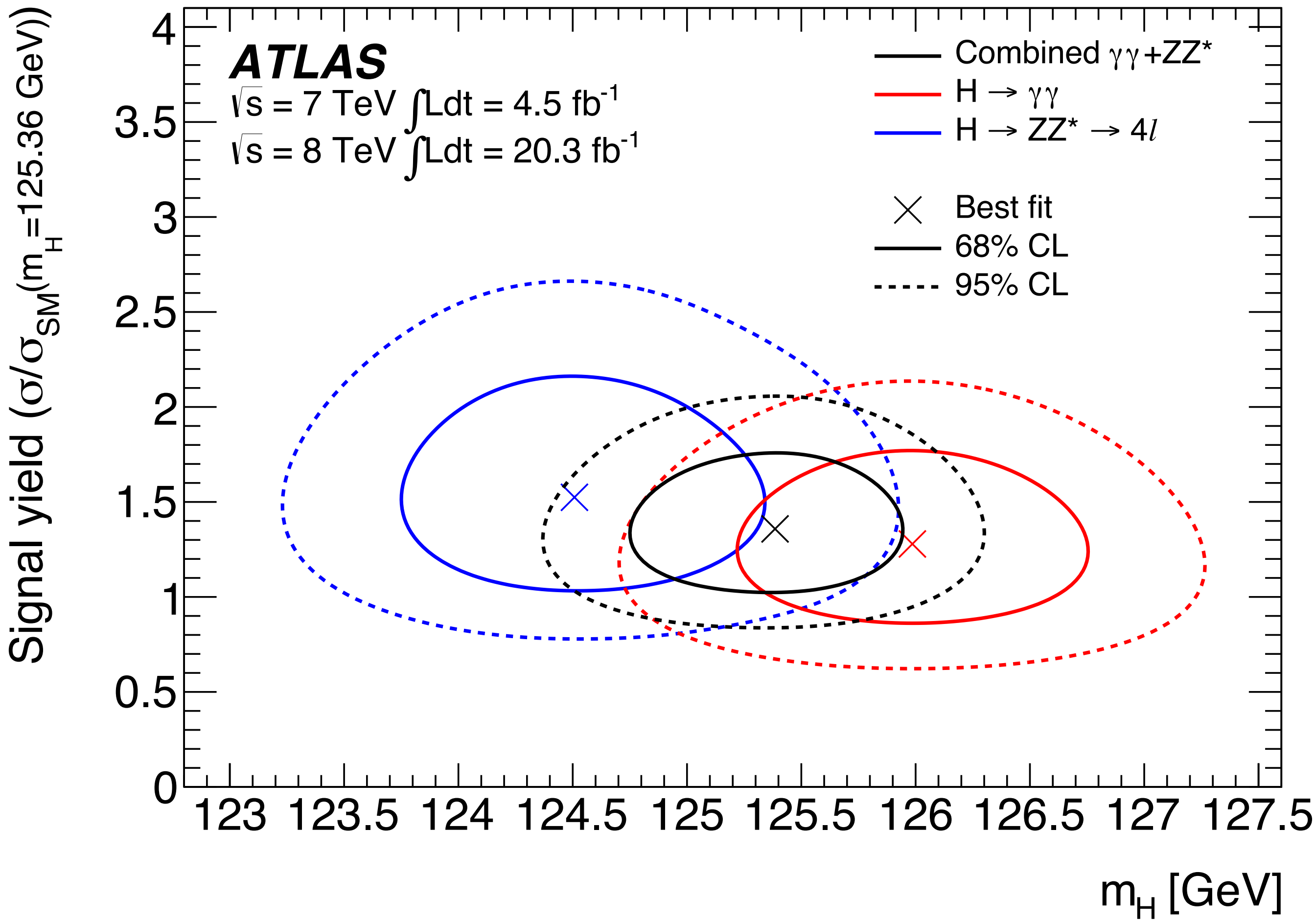
Phys. Rev. D 89, 092007 (2014)

Validation of per-event mass resolution

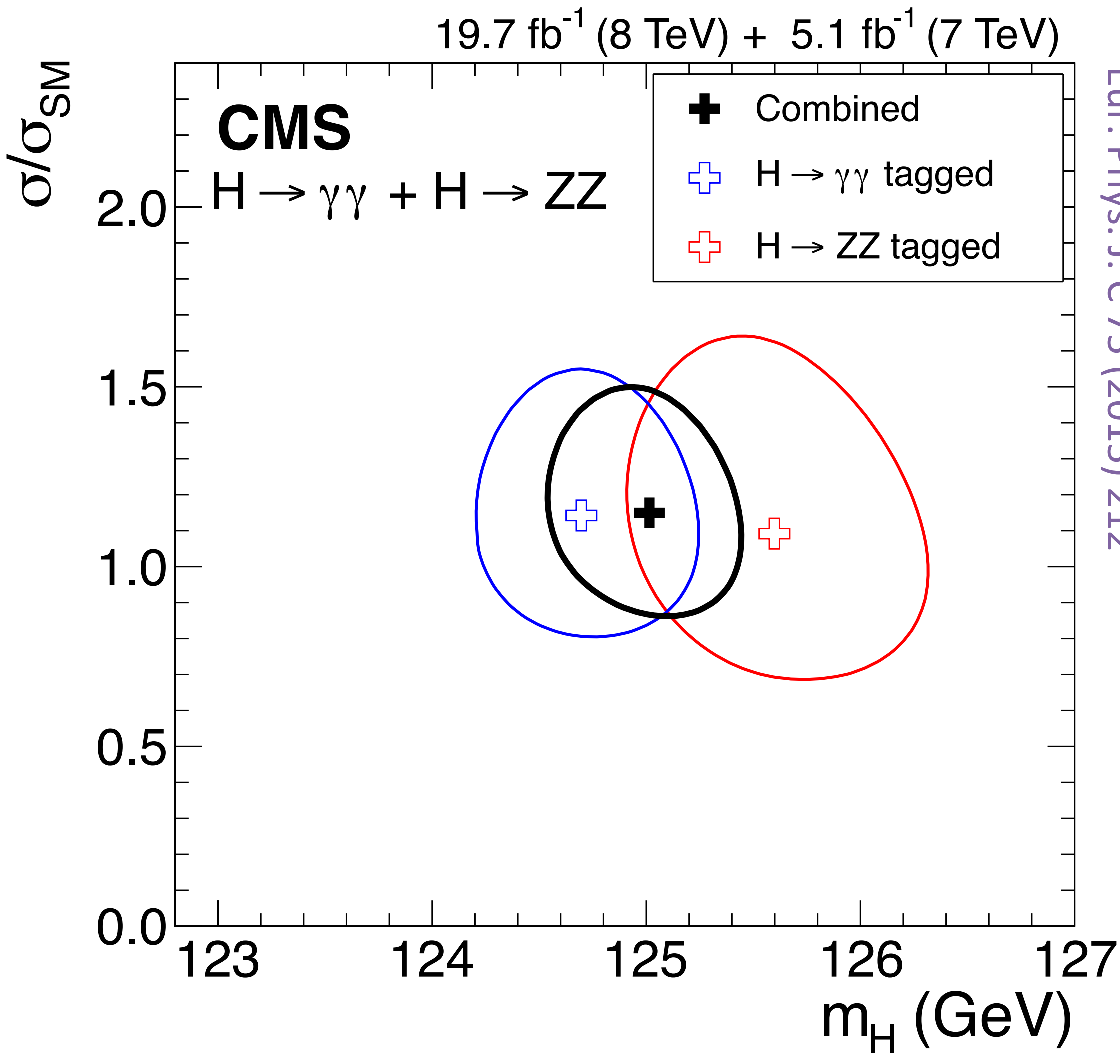


γγ+4l

Phys. Rev. D 90, 052004 (2014)



γγ+4l

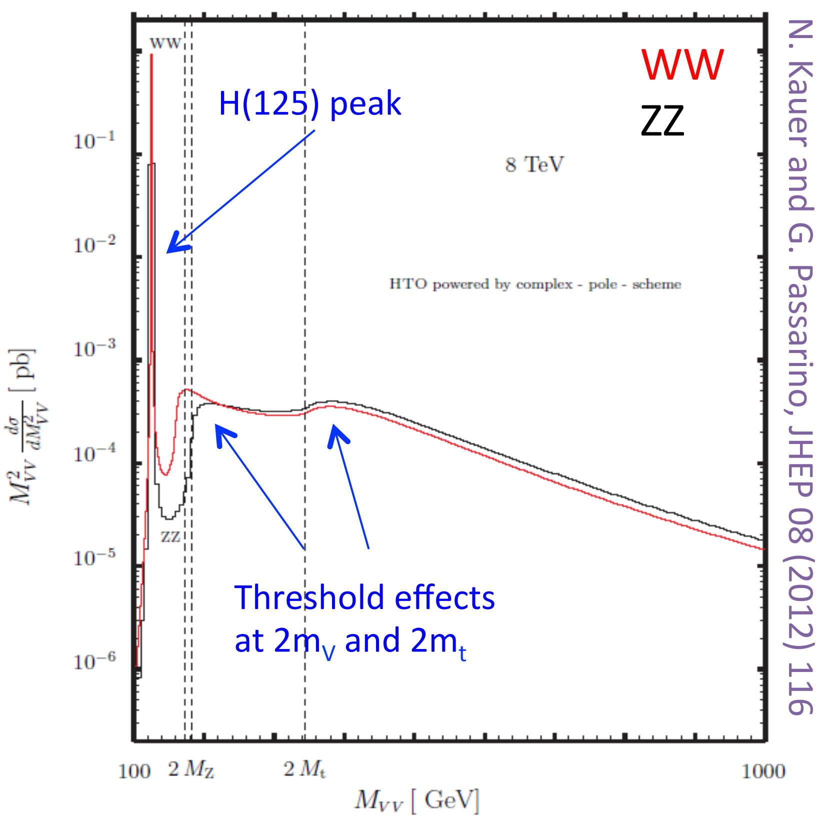


Eur. Phys. J. C 75 (2015) 212

Offshell decays and H width

- Non-negligible offshell contribution to H(*) ⟶ VV cross section (V = W, Z)

gluon-gluon fusion production



- In SM, Γ_H= 4.1 MeV << experimental resolution on mass peak (1-3 GeV)
- In SM, the ratio of off-shell and on-shell cross sections is proportional to Γ_H

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

- Can off-shell decays help constrain Γ_H ?

Fit offshell signal strength μ^{off} to data in m_{ZZ}>200 GeV region

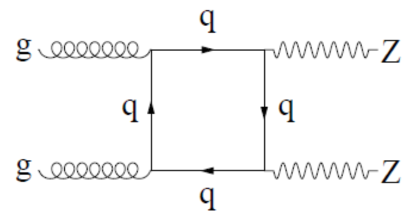
- μ^{off} sensitive to modification in couplings:

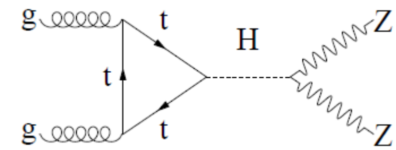
$$\mu_{\text{off-shell}}(\hat{s}) = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

- μ^{off}/μ^{on} can be interpreted as Γ_H/Γ_{SM} if couplings depend on m_{ZZ} as in SM

$$\mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

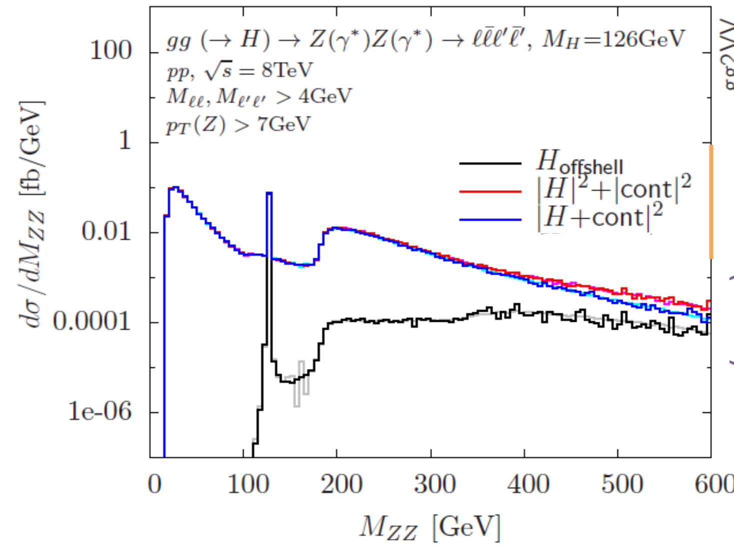
Interference effects





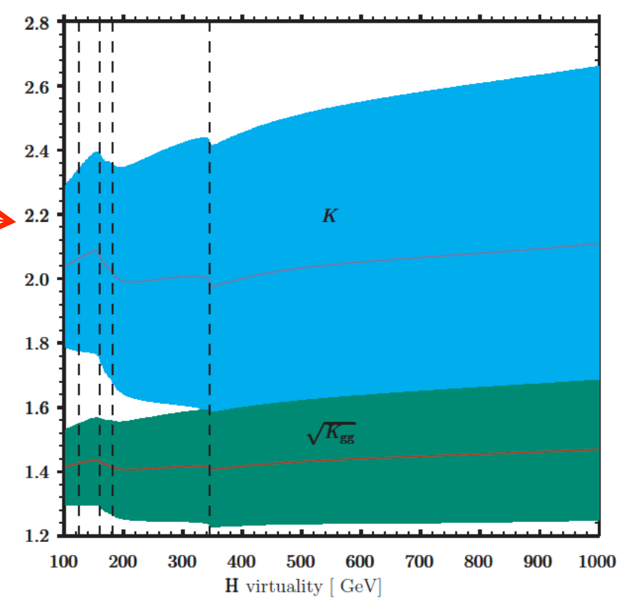
- Negative interference with gg->VV background
  - large at high m_{VV}
- Accounted for in offshell distribution

$$\mathcal{P}_{\rm tot} = \mu_{\rm off}\mathcal{P}_{\rm sig} + \sqrt{\mu_{\rm off}}\mathcal{P}_{\rm int} + \mathcal{P}_{\rm bkg}$$



N. Kauer and G. Passarino, JHEP 08 (2012) 116

- In gg fusion production, background and interference only calculated at LO
  - Signal m_{VV}-dependent k-factors (NNLO/LO) applied G. Passarino (Eur. Phys. J. C 74 (2014) 2866)
  - Based on results from M. Bonvini et al. (Phys. Rev. D88 (2013) 034032) and K. Melnikov and M. Dowling (arxiv1503.01274), assume $k_{\rm continuum} = k_{\rm signal}$ as central value



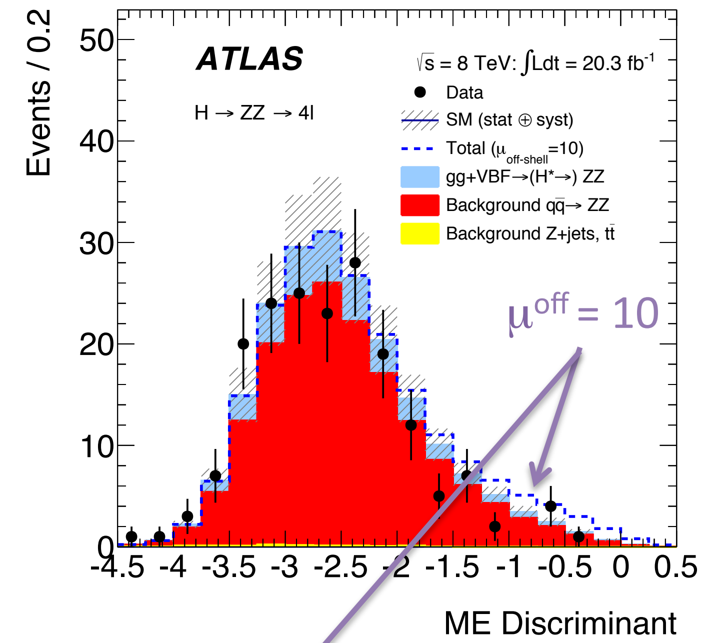
G. Passarino, Eur. Phys. J. C 74 (2014) 2866

Eur. Phys. J. C (2015) 75:335

Analysis

- H->ZZ->4l channel
  - Matrix-element discriminant targetting H^{0+}

$$\mathrm{ME} = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

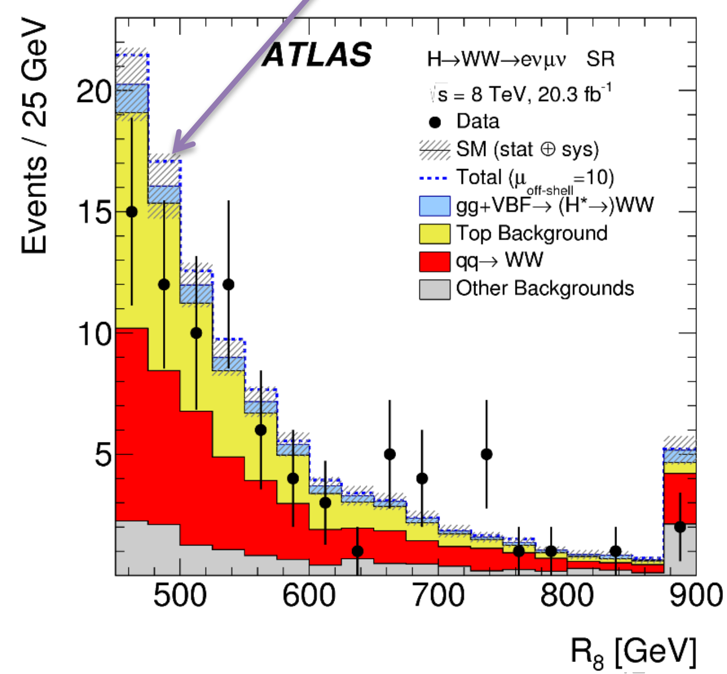


- H->ZZ->2l2ν channel
  - Only in off-shell region
  - Discriminant: transverse mass m_T

$$m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left(\sqrt{m_Z^2 + \left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}\right)^2 - \left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

- H->WW->eμ2ν channel
  - Discriminant: R_8 combination of dilepton mass and m_T^{WW}

$$R_8 = \sqrt{m_{\ell\ell}^2 + \left(a \cdot m_{\mathrm{T}}^{WW}\right)^2}$$



- Channel combination assuming same κ_g, κ_V in ZZ and WW channels

Eur. Phys. J. C (2015) 75:335

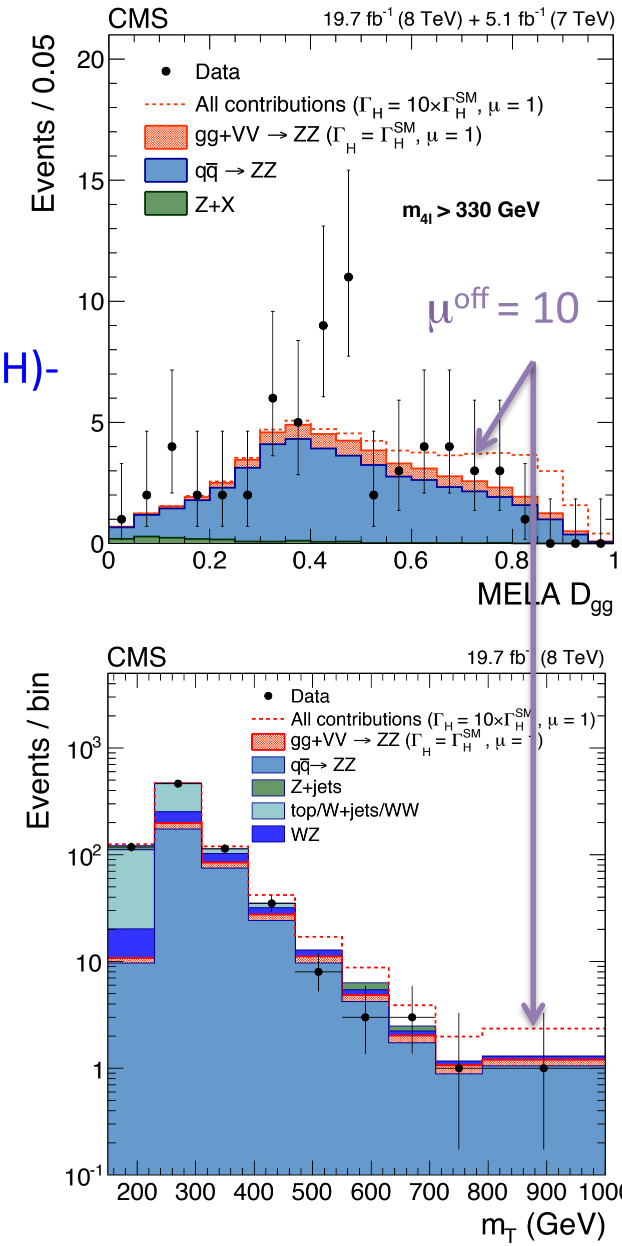
Systematic uncertainties

Systematic uncertainty	95% CL lim. (CL_s) on $\mu_{\text{off-shell}}$
Interference $gg \to (H^* \to) VV$	7.2
QCD scale $\text{K}^{H^*}(m_{VV})$ (correlated component)	7.1
PDF $q\bar{q} \to VV$ and $gg \to (H^* \to) VV$	6.7
QCD scale $q\bar{q} \to VV$	6.7
Luminosity	6.6
Drell–Yan background	6.6
QCD scale $\text{K}^{H^*}_{gg}(m_{VV})$ (uncorrelated component)	6.5
Remaining systematic uncertainties	6.5
All systematic uncertainties	8.1
No systematic uncertainties	6.5

Analysis

- Baseline Phys. Lett. B 736 (2014) 64
  - H->ZZ->4l channel
    - ME-based discriminant (D_{gg}) targetting total gg(->H)->ZZ production; fit to (D_{gg}, m_{4l})
    - Dijet category in on-shell region
  - H->ZZ->2l2ν channel
    - Discriminant: transverse mass m_T
  - Fit μ^{on}_{ggF}, μ^{on}_{ggF} and Γ_H/Γ_{SM}
- Update in H->ZZ->4l channel arXiv:1507.06656
  - Dijet category added in offshell region; fit also μ^{off}_{VBF}
  - Allows to search for a mass-dependent HVV anomalous coupling Λ_Q

$$A(\mathrm{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{\mathrm{V}1}+q_{\mathrm{V}2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{\mathrm{V}1}^2+q_{\mathrm{V}2}^2)}{(\Lambda_1)^2} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

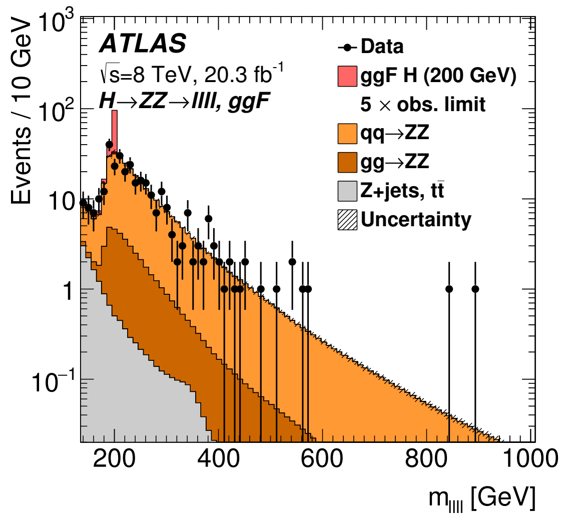


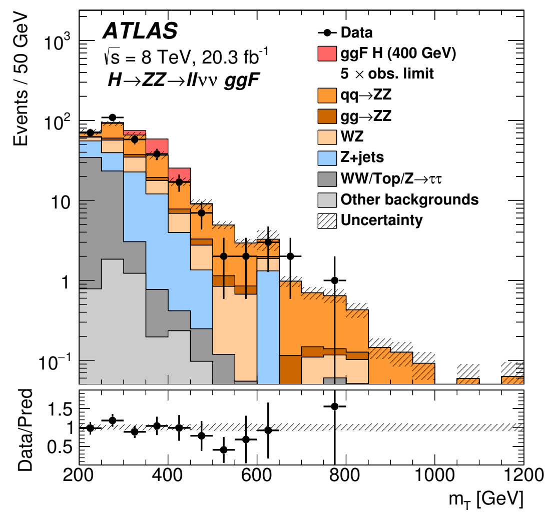
arXiv:1507.05930

H→ZZ

ZZ→ℓℓℓℓ

- 140-1000 GeV
- 4e, 4μ, 2e2μ
- ggF, VBF, VH categories
- Discriminant: m_{4l}



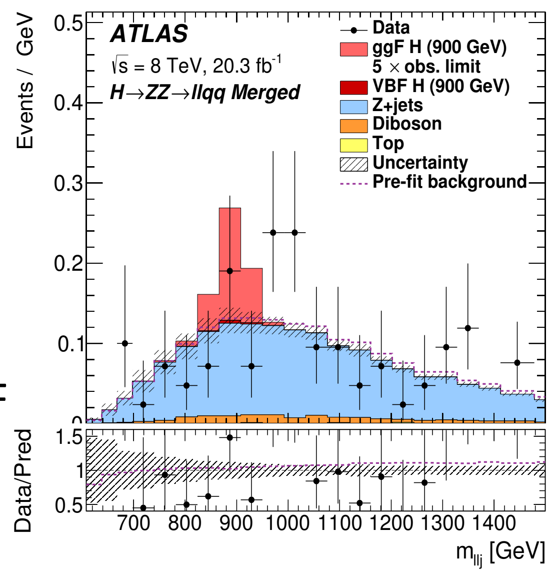


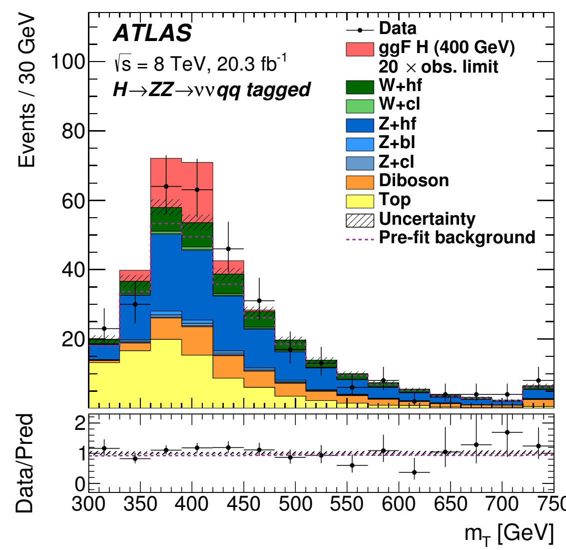
ZZ→ℓℓνν

- 200-1000 GeV
- eeνν, μμνν
- ggF, VBF
- Discriminant: m_T

ZZ→ℓℓqq

- 200-1000 GeV
- eeqq, μμqq
- Resolved ggF (<2, 2 b-tags), ggF merged jets (>700 GeV), VBF
- Discriminant: m_{lljj}



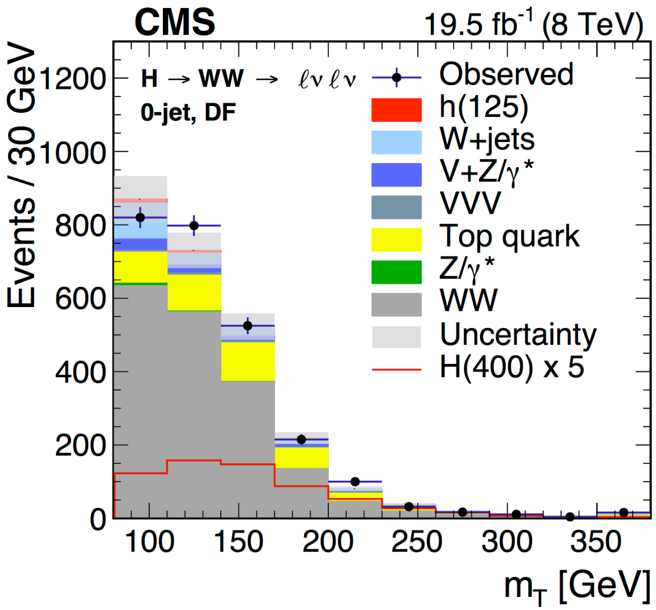


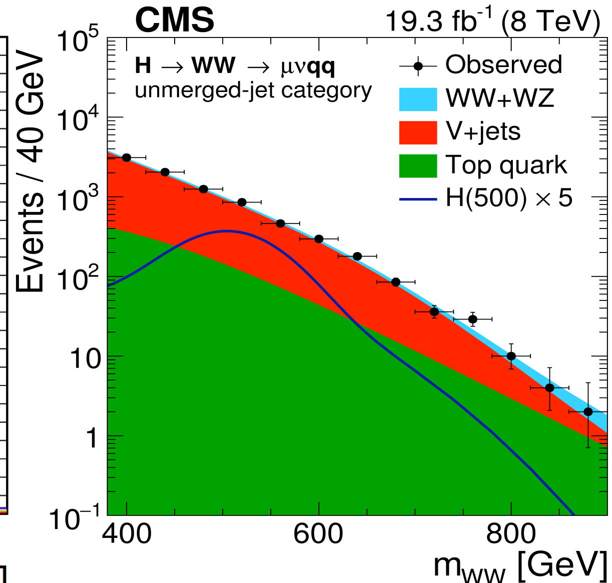
ZZ→ννqq

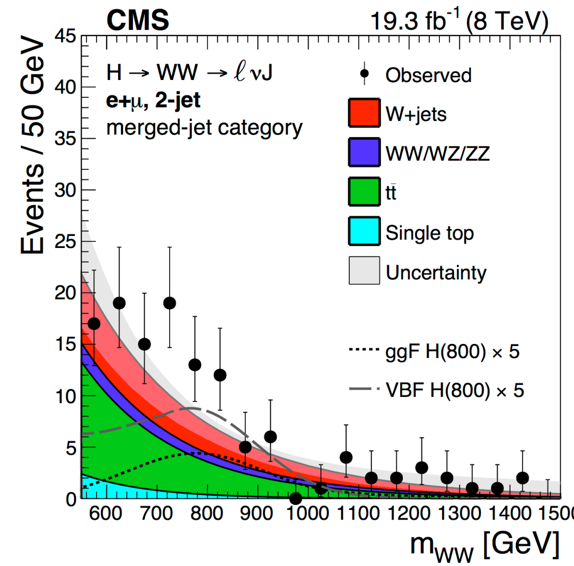
- 300-1000 GeV
- <2, 2 b-tags
- Discriminant: m_T

arXiv:1504.00936

H→WW







WW→ℓνℓν

- 145-1000 GeV
- ee, μμ, eμ
- 0,1 jets, VBF
- res(m_H)~20%

WW→ℓνjj

- 180-600 GeV
- eνjj, μνjj
- Inclusive
- res(m_H)~5-15%

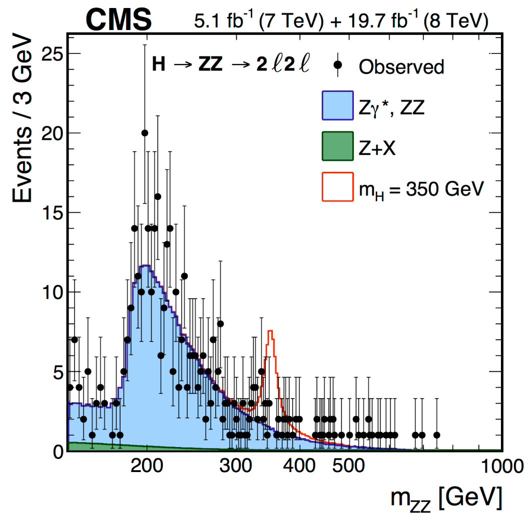
WW→ℓνJ

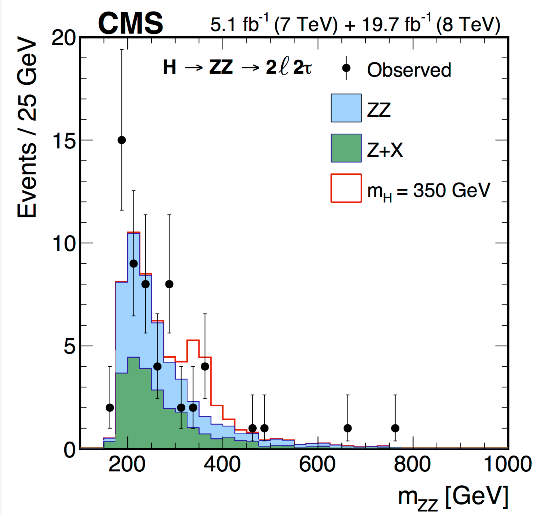
- 600-1000 GeV
- eνJ, μνJ
- 0+1 jets, VBF
- res(mH)~5-15%

arXiv:1504.00936

H→ZZ

ZZ→ℓℓℓℓ
- 145-1000 GeV
- 4e, 4μ, 2e2μ
- untagged, VBF
- res(m_H)~1-2%

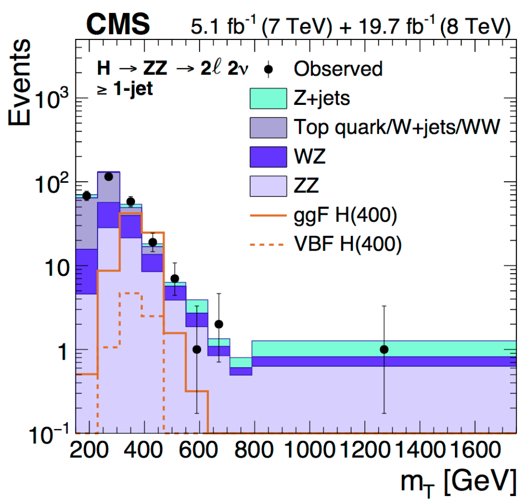


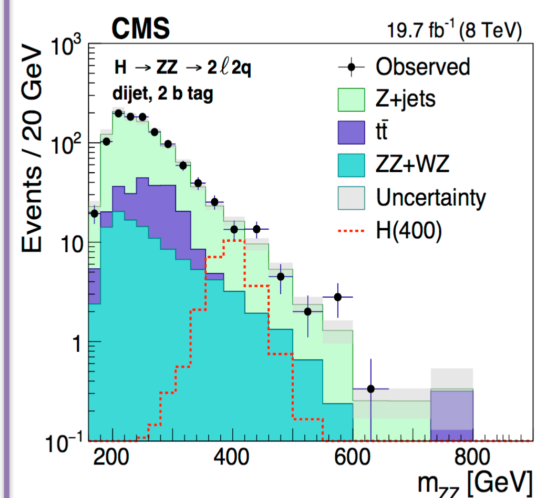


ZZ→ℓℓττ
- 200-1000 GeV
- eeττ, μμττ

($\tau_h\tau_h$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_\mu$)
- untagged
- res(m_H)~10-15%

ZZ→ℓℓνν
- 200-1000 GeV
- eeνν, μμνν
- 0, ≥1 jets, VBF
- res(m_H)~7%



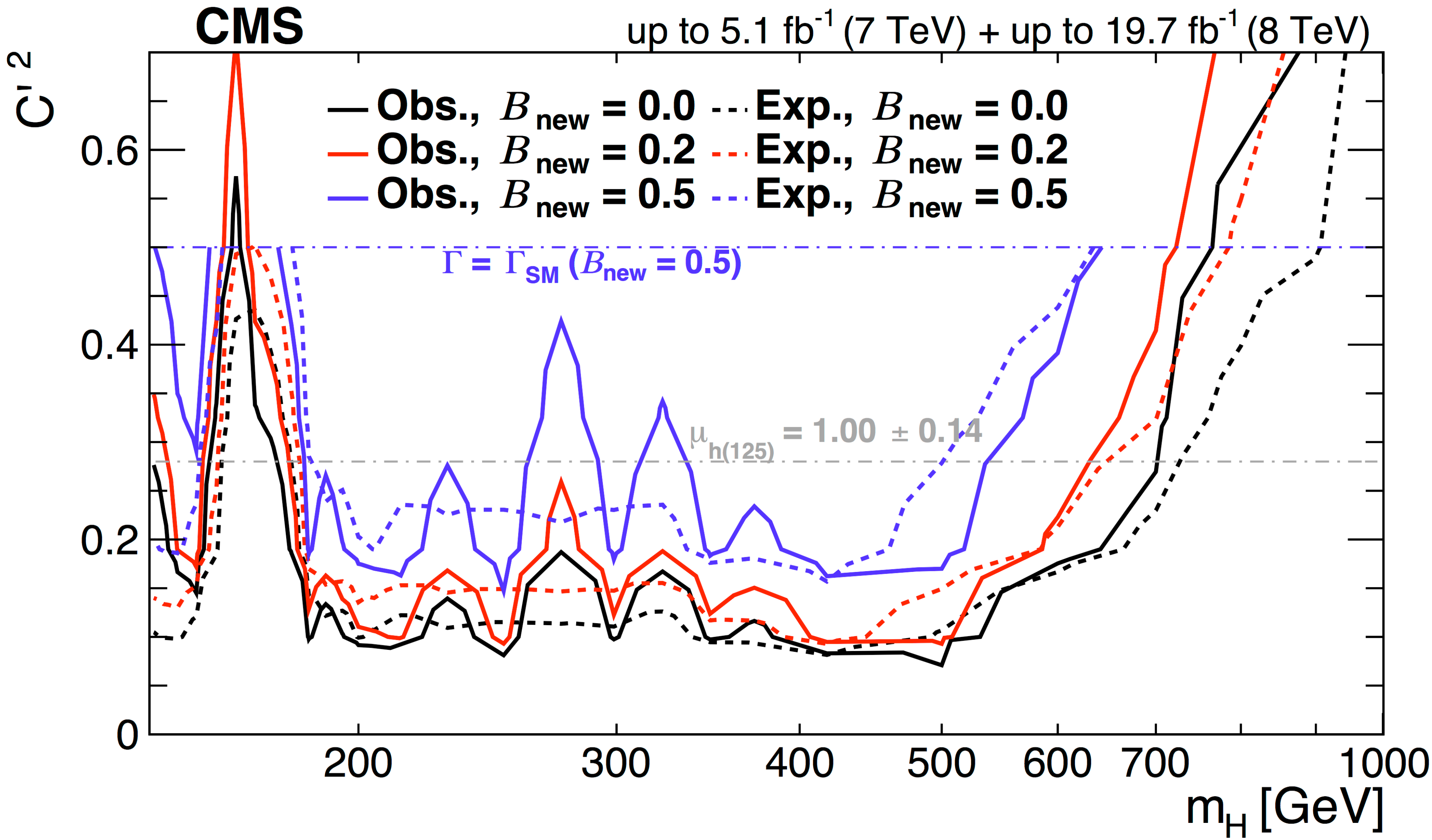


ZZ→ℓℓqq
- 230-1000 GeV

(Merged jets >600 GeV)
- eeqq, μμqq

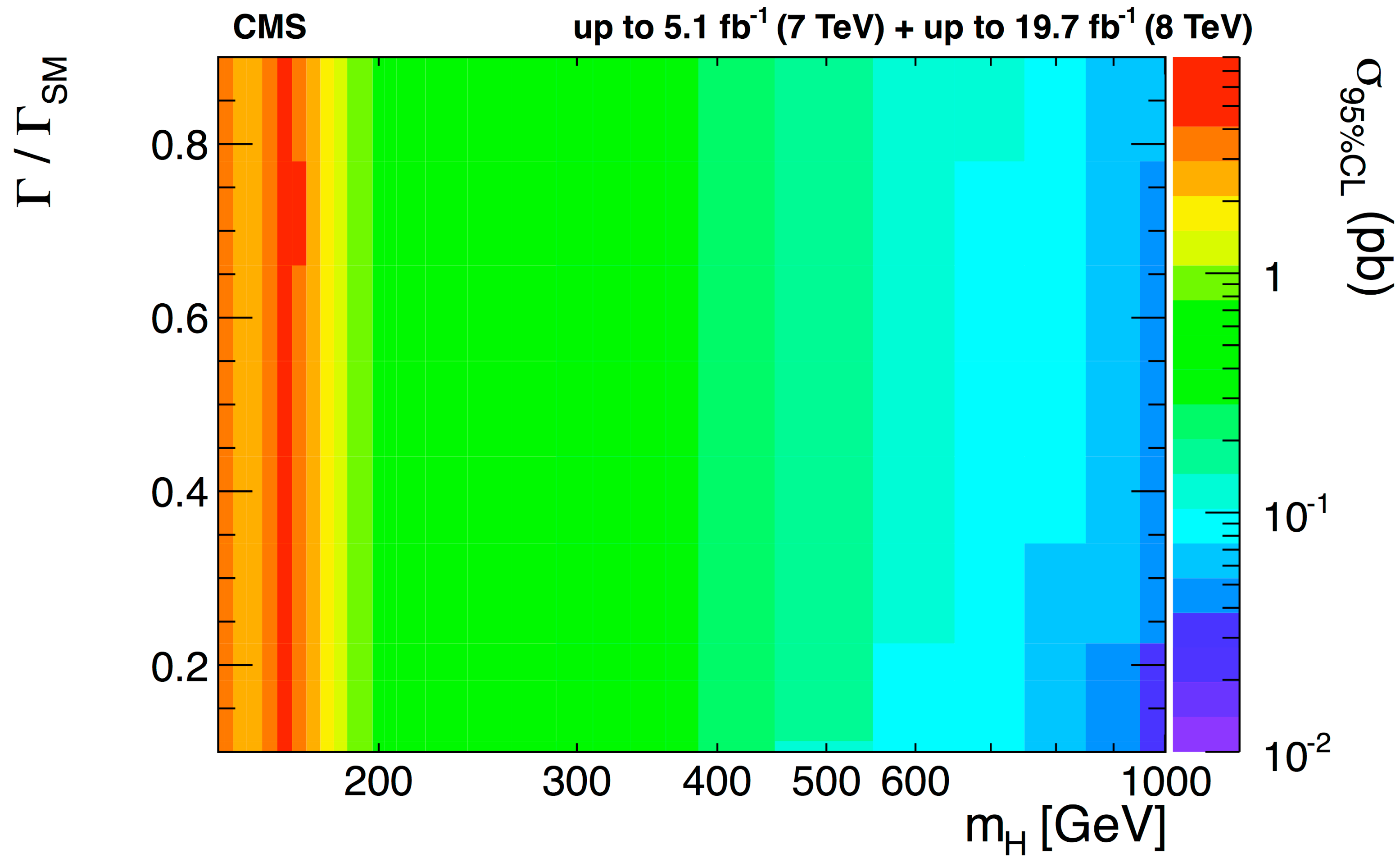
(0, 1, 2 b-tags)
- untagged, VBF
- res(m_H)~3%

C'^2 limits with the full high mass search combination



Generic (m_H, Γ) scan assuming VBF to ggF scaling as in SM

arXiv:1504.00936



Split into ggF and VBF

arXiv:1504.00936